HUNGER SIGNS IN CROPS

A SYMPOSIUM

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Prepared by

S. A. BARBER
JOHN C. CAIN
R. L. CAROLUS
JAMES A. COOK
LEROY DONALD
G. V. C. HOUGHLAND
ROGER P. HUMBERT
WINSTON W. JONES
B. A. KRANTZ
J. E. McMURTREY, Jr.
S. W. MELSTED
WERNER L. NELSON
E. R. PURVIS
W. R. SCHMEHL
NELSON SHAULIS
C. B. SHEAR
CARTER R. SMITH
PAUL F. SMITH
HOWARD B. SPRAGUE
W. W. WOODHOUSE, Jr.

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Foreword to the Third Edition

THE first (1941) and second (1949) editions of "Hunger Signs in Crops" enjoyed wide acceptance and use. This third edition presents similar concise, lucid, and accurate descriptions of the visible symptoms of nutrient deficiencies in economic crops. Much has been learned about plant nutrition in the decades since the first edition was prepared, and knowledge on all aspects of plant response to nutrient elements doubtless will continue to accumulate.

The original 19 authors of the first 2 editions of "Hunger Signs" made a monumental contribution to better understanding of nutrient deficiencies of crops, and detection and interpretation of visible deficiency symptoms. Six of them participated in preparing this third edition. Associated with them are 14 new authors, each of whom has the intimate scientific knowledge required for this revision.

All 20 authors have undertaken to maintain in this volume, the accuracy and readability of earlier editions. They have recognized that profound changes have occurred since 1945 in the production of economic crops. Increases in acre yields, new varieties, and improved cultural practices have accentuated crop demands for mineral elements. Native supplies of plant nutrients in the soil hardly are adequate anywhere for present levels of crop production, and high dependence must be placed on the addition of fertilizers and soil amendments to maintain healthy growth. Thus, the appearance of "hunger signs" indicating nutrient deficiences has become an increasingly important matter.

Revisions in the text of this third edition, presenting current knowledge in non-technical, readily understandable form, are substantial. For example, in Chapter I some 30 insertions totaling 2000 words were necessary to bring the text up-to-date. Chapter II on corn and small grains was rewritten to cover problems on alkaline and irrigated soils, and a new section on grain sorghums has been added. Chapter IX on tree fruits and nuts is essentially new, with all new color plates. Three completely new chapters on forages, small fruits, and sugar crops have been added, thus giving more complete coverage of economic crops grown in temperate and sub-tropical regions.

All of the chapters appearing in earlier editions have been revised in text, illustrations, and color plates to present the current status of knowledge on each crop. They include much added information on es-

sential trace elements—zinc, molybdenum, copper, manganese, iron, and boron—that have become increasingly important in crop production. Occurrence of deficiencies in calcium, magnesium, and sulfur, has increased in the last decade; thus, more attention is given to them, without neglecting the major elements—nitrogen, phosphorus, and potassium.

The extent of this revision may be noted from the increased number of pages—up by 20 percent, the increased number of black and white illustrations—up by 10 percent, and the increased number of color illustrations—up by 45 percent. Sixty-eight of the black and white illustrations and 114 of the color illustrations are new.

An outstanding and unique feature of "Hunger Signs in Crops" has been its plates showing symptoms of nutrient deficiencies in natural colors. This third edition has 110 pages of color, presenting 193 full color illustrations. These illustrations reveal more clearly than is possible by any other means, deficiency symptoms on each major crop plant for each essential nutrient element. Descriptions given in the accompanying text of each chapter provide explanations of the causes and correction of nutrient deficiencies. This combination of true-to-life color illustrations and accompanying discussion and explanation provides a better basis of understanding of the nutrition of plants and how they function in the field.

This third edition differs from previous ones in that it is the product of a commercial publisher, The David McKay Company, Inc. The National Plant Food Institute and the American Society of Agronomy, who have transferred their copyrights to the McKay Company, have been most helpful in advising on the preparation of this edition. The authors of each chapter, who are specialists in these fields of plant nutrition, have distilled their accumulated knowledge into this book. They hope "Hunger Signs in Crops" will not only continue to serve agriculture in North America, but find use in other comparable climatic regions of the world.

HOWARD B. SPRAGUE
Editor, Third Edition

University Park, Pa.
June 1964

Foreword to the Second Edition

When "Hunger Signs in Crops" was first projected, those who cooperated in preparing the book believed they would be offering the agricultural public a much-needed treatise on the subject. Although rapid advances had been made by agricultural scientists in the study of nutrient-deficiency symptoms in crops, their work had not been assembled in convenient form.

As in all such ventures, there was much uncertainty about the reception such a book would be accorded. Concern on this point was soon dispelled. Immediately after its announcement, orders began pouring in. Three printings were required, and high praise for the volume came from numerous organizations and individuals. The book was widely used by college professors, research and extension specialists, industrial chemists and agronomists, county agents, and teachers of vocational agriculture. Many farmers found it of much use in deciding on their fertilizer program.

Rapid advances have been made in our knowledge of this subject, so that it has become necessary to prepare an entirely new edition. This second edition includes much material that has not previously been published. Many hours of unselfish labor have been devoted by the chapter authors to the revision. Credit is due also to their associates and colleagues who have offered suggestions and furnished photographs.

Accordingly, the American Society of Agronomy and the National Fertilizer Association are now pleased to present to the public this second edition of "Hunger Signs in Crops." We hope it will continue to serve the cause of an ever better American agriculture.

Firman E. Bear, *President*
American Society of Agronomy
Russell Coleman, *President*
The National Fertilizer Association

Washington, D. C.
September 1949

Foreword to the First Edition

When we human beings lack certain essential nutritive elements, we get serious nutritional diseases—rickets from a lack of calcium, phosphorus, and vitamin D; nutritional anemia from a lack of iron; beriberi from a lack of thiamin; pellagra from a lack, probably, of nicotinic acid; scurvy from a lack of ascorbic acid; and so on through a considerable list. The symptoms of these diseases are pretty clearly recognized by physicians.

Even when there is no acute disease, an essential nutritive element may be sufficiently lacking to give us a borderline case—some minor but perhaps troublesome ailment that keeps us from being really healthy. Frequently these borderline ailments too can be diagnosed by the shrewd eye of the physician, sometimes supplemented by laboratory tests.

Much of this knowledge is new, and it is of untold value. It means that many human ills—even many untimely deaths—can now be considered absolutely needless; much of our common inability to meet the demands of life with full nervous and physical vigor can be eliminated.

Best of all, we do not have to depend on the physician to achieve these things for us. As the modern knowledge of nutrition spreads, anyone who will take the trouble to understand and use it has the control of life and health, insofar as they are affected by food, within his own hands.

At the same time, farmers are now better able to feed their livestock for maximum health and productiveness because knowledge of human and animal nutrition have advanced together.

What has all this to do with the subject of fertilizers and crop plants?

There is a close connection in more ways than one. Plants too are living things. They take in food and convert it into body tissues and energy; they can be healthy and vigorous or they can be ill and die; they have their acute diseases and their minor ailments; and they require certain nutritive elements just as surely as do we human beings. Many of these elements, in fact, are the same ones we require. Without them, the plant too suffers from hidden hunger. It needs a balanced diet as much as we do.

You cannot tell a plant to stick out its tongue and say "Ah," but there are other ways of examining it for symptoms of ill health. It may show unmistakable signs of hidden hunger—nutritional deficiency—if we can only recognize them.

The purpose of this book is to help us to recognize the signs of nutritional deficiency in crop plants. It was written by scientists who have made a close study of this subject, each in his own particular field, for many years.

As in the case of human nutrition, the best thing about this knowledge is that it is not all in the hands of the experts; it can be used by the layman. The farmer who will take the trouble to study the symptoms of malnutrition in plants is in a position, in many cases, to correct the difficulties himself.

Much of this knowledge also is new. A few years ago, for instance, what farmers called "firing" of corn was attributed to drought. Now it is known that though firing of corn is made worse by lack of moisture, it is fundamentally due to nutritional deficiencies—shortage of essential elements in the food supply of the plant.

And just as one nutritional element after another was found to be vitally necessary for human health, so one element after another was found to be essential for the health of plants. There is a real parallel between the discoveries in these two fields.

After it was found that lack of one or another plant food could cause definite nutritional diseases in plants, the next step was to make a close study of the symptoms. A number of scientists have been doing this in the United States and other parts of the world for many different kinds of plants and many plant foods. They have used field studies, plot studies, pot studies, and nutrient-solution studies.

The work requires great patience and a close knowledge of what the plant is like in normal health. The scientist notes down every visible effect or symptom in a plant deprived of this or that element, being careful not to be fooled by something that is not a symptom. Then he tries to put the complicated lot of symptoms into some order and describe them with the utmost accuracy so they will be understandable and useful in diagnosis.

That is what has been done in this book for a considerable number of important crops.

Some of the chapters include a key for quickly identifying a deficiency by its symptoms. These keys are arranged in the form sometimes used for plant identification, with all coordinate headings marked by the same letter, rather than in ordinary outline form. There is also a wealth of illustrations in color and in black and white. With the accompanying legends, they are intended to tell as complete a story as possible by themselves.

The book is not to be considered as the final word by any means. Active work is still going on in this field, and much remains to be done. The reader will note, for instance, that there is not as complete or as definite information about all deficiencies in some crops as in others—sometimes because of inherent difficulties, sometimes because less research work has been done in the latter cases.

Thus, the farmer will need to use caution in diagnosing deficiency symptoms, and where there are uncertainties he will want to get expert help from scientific workers. He should be especially careful about confusing deficiency symptoms with conditions due to disease, organisms, insects, or other causes.

In a few cases, injuries caused by excesses of certain elements are mentioned in the text or illustrated in figures, but no attempt has been made to cover this subject systematically.

Now a brief account of how the book came to be written.

Early in 1936, The American Society of Agronomy felt that enough is known about the symptoms of malnutrition in plants—though there is much yet to be discovered—to prepare a monograph on the subject, and that such a monograph would fill a growing need. The Committee on Fertilizers, headed by R. M. Salter, appointed a subcommittee to look into the possibilities, with J. E. McMurtrey, Jr., as chairman. As a first step, this group got the assistance of the Plantfood Research Committee of The National Fertilizer Association in rounding up all available colored photographs of malnutrition symptoms, and these were exhibited at the 1936 meeting of the Society of Agronomy.

Early in 1937, plans were outlined for the book, "Hunger Signs in Crops," and the authors were selected. A major problem from a practical standpoint was to keep the price from being prohibitive; it would be very high for a small edition of a book with as many colored illustrations as were needed in this case to give maximum usefulness. However, the authors, as members of The American Society of Agronomy, contributed their work without compensation; Charles J. Brand and H. R. Smalley contributed much time and effort that would ordinarily have been part of overhead expenses; and The National Fertilizer Association, through its Soil Improvement Committee, agreed to be responsible for the sale of enough copies, in addition to the ordinary demand, to make a fairly large printing possible and thus materially reduce the cost per copy. (While these acknowledgments are being made, credit should also be given to Marion J. Drown for a great deal of detailed editorial work on the chapters, and to Mary A. Bradley for indexing.)

So wide a range of material on malnutrition symptoms in plants has not before been brought together in a single volume, and it should be useful alike to farmers, students and teachers of agriculture, technical workers, and everyone concerned with the proper management of soils and crops. Care has been taken to keep the book as nontechnical as possible so as to give it wider usefulness. Even the usual lengthy bibliographies have been cut down to a few references. Fertilizer analyses, however, appear throughout the book in the technical form. This is so familiar to farmers and others concerned with agriculture that it hardly needs explanation. In such an analysis (4-10-6, for example) the first figure stands for the percentage of nitrogen (N) in the total mixture, the second for the percentage of available phosphoric acid (P_2O_5), and the third for the percentage of available potash (K_2O).

The editor would be remiss if he did not emphasize one other reason why he thinks the book is important aside from the main point, which, of course, is its immediate practical value. It marks one more step in the study of nutrition from the soil on up through man. What the soil does not have, plants will not get, and animals and men will lack also. The welfare of man is intimately bound up with the welfare of soils and plants because all our food comes in the first instance from plants; even our meat, milk, eggs, and fish are simply plant substances rebuilt into other forms.

There is a vastly significant story here which we can see as yet only in dim outline. Much more will be heard about it as time goes on, and everything that will help to fill in the many gaps in the story is a contribution to human welfare.

GOVE HAMBIDGE
(*Editor,* First Edition)

Washington, D.C.
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Why Do Plants Starve?

By Howard B. Sprague *

NO ONE worries about healthy plants. But when plants fail to grow vigorously, farmers become concerned. A plant will slow down in rate of development or will show other signs of trouble whenever any of the many factors that contribute to its well-being gets out of balance. The Indian learned that burying a fish under a corn hill produced better plants, and that corn grew better where a brush pile had been burned. The Indian did not realize that he fertilized the soil with nitrogen and phosphate from the fish and with potash from the wood ashes. Other necessary elements also were provided by the fish and the ashes. What they were did not matter so long as fish and ashes were plentiful and not much corn was needed.

THE PLANT NUTRIENTS

Since corn is widely known, let us use it to obtain a picture of the materials that such a plant requires for its growth. It will be helpful, as background for a better understanding of the articles in this book, to have a clear conception of the kinds and amounts of materials required to produce 100 bushels of corn.

The plants producing 100 bushels of corn on 1 acre of land, a fairly high yield, consist of about:

4,000 pounds of stover
1,400 pounds of cobs
5,600 pounds of shelled corn
5,200 pounds of roots and stubble

—a total of about 16,200 pounds of air-dry matter. Excluding all water, this amounts to about 14,200 pounds of moisture-free crop growth.

* In the earlier editions of this book, Chapter 1 was written by George D. Scarseth, Director of Research, American Farm Research Association, and Norman J. Volk, Director, Purdue University Agricultural Experiment Station.

Sources and quantities of raw materials needed to produce this amount of dry material appear in the following list:

Source	Substance*	Chemical Symbol	Pounds per Acre	Approximate Equivalent
Furnished by air and water; equal 95% of plant weight	Water	H_2O	4,300,000 to 5,500,000	19 to 24 inches of rain
	Oxygen	O_2	6,800	Air is 20 percent oxygen
	Carbon	C	5,200 carbon or 19,000 carbon dioxide	Amount of carbon contained in 4 tons of coal
Major mineral nutrients from soil or fertilizers and lime	Nitrogen	N	130	4 100-pound bags of a 32 percent nitrogen fertilizer
	Phosphorus	P	22	2½ 100-pound bags of 20 percent superphosphate
	Potassium	K	110	2 100-pound bags of 60 percent muriate of potash
	Sulfur	S	22	22 pounds of yellow sulfur
	Magnesium	Mg	33	330 pounds of Epsom salts
	Calcium	Ca	37	93 pounds of limestone
Essential trace elements needed in small amounts by plants	Iron	Fe	2	2 pounds of nails
	Manganese	Mn	0.3	1 pound of potassium permanganate
	Boron	B	0.06	¼-pound box of common borax
	Chlorine	Cl	Trace	Enough in the rainfall
	Iodine	I	Trace	1-ounce bottle of tincture of iodine
	Zinc	Zn	Trace	The shell of one dry-cell battery
	Copper	Cu	Trace	25 feet of No. 9 copper wire
	Molybdenum	Mo	Trace	1 ounce of sodium or ammonium molybdate

* The analyses for nitrogen, potassium, phosphorus, magnesium and calcium were made on corn at Lafayette, Ind., in 1938, 1939 and 1940. The other figures are from various sources. The composition of corn plants varies on soils of different levels of fertility, and that of other types of crops varies from that of corn in minor details.

Evidently plants require vital nutrients in widely differing amounts. Each substance also has its own peculiarities. Some, for example, may be present in the soil in plentiful quantities yet be unavailable because they are tied up in chemical compounds that the plants cannot use. In order to have a better understanding of what these nutrients do for plants and why plants may starve for lack of them, let us review a few facts about each.

WATER (H_2O)

From the rootlets that reach into the soil to the tips of the most remote leaves, a plant is one continuous water pipe. The solid structures of plants are made up of cells filled with delicately organized gel-like substances (colloids) that have a great attraction for water. This attrac-

tion pulls water into plants with such a strong force that almost 99 percent of certain parts of cells may be water—water that has been extracted from soil bearing perhaps only 15 or 20 percent moisture by weight. Plant root hairs absorb nearly all of the water taken from the soil.

The water system in a plant is the medium through which nutrients pass, whether upward from the roots or downward from the leaves, to the proper plant compartments. Here they are built into such foods as sugars and amino acids (the building materials of protein), which in turn are transformed into cellulose and other compounds that make up the solid structures of the plant. Any by-products or excess materials can be carried out of plants by water and excreted back into the soil or into the air. In fact, roots give off carbon dioxide that in solution with water forms a weak acid that aids in dissolving minerals in the soil.

The normal functioning of a plant cell depends on an adequate intake of water so that turgor (normal tension or rigidity) can be maintained and the tissue-building process can proceed. Since water is continually passing out of a plant, as water vapor through the stomata or breathing pores of the leaves, turgor depends on the maintenance of a delicate balance between intake of water through its roots and outgo through its leaves. Cell sap contains various salts that exercise a "pull" on water, so that it passes from a zone of low salt concentration in the soil to one of high salt concentration inside the plant cells, a process called osmosis. An excessively high salt concentration in the soil near the roots, resulting from too localized an application of fertilizer, or from saline or alkali salts in dry regions, may upset this process and cause plants to lose water to the soil instead of absorbing it. The turgor of their cells then decreases and the plants wilt.

Any slight decrease in turgor upsets the machinery inside the leaf, and some symptoms that resemble malnutrition may show up. Thus, the appearance of plants may suggest shortage of nitrogen, potassium, or some other element. In fact, actual starvation may occur, for conditions that cause plants to suffer for water also may affect the availability of nutrients and their accessibility to the roots. Roots are dependent on the movement of plant nutrients in the soil moisture. The movement of nutrients in the soil decreases as soil moisture becomes depleted.

OXYGEN (O)

Fortunately the earth is blessed with a liberal supply of oxygen, which is as vital to plants as it is to man. Growers seldom realize that approxi-

mately 50 percent of the dry matter in plants is oxygen. It combines with the other elements shown in the list to form oxides and complex organic compounds. When a plant is functioning in full vigor and health, a shifting and balancing of oxygen occurs between elements that are being rearranged into plant-tissue parts. This shifting of the oxygen is called oxidation when it involves adding oxygen, and reduction when it involves taking away of oxygen.

In certain reduced forms, some elements become poisonous to plants. Two such poisons that are very common are the nitrites and sulfites. In their oxidized forms—that is, with oxygen added—these become nitrates and sulfates, which are nontoxic. In general, reduction of compounds is as necessary as oxidation in healthy plants, because some compounds, such as the nitrites, are reduced still further for use in building proteins.

Any upset in the balance of oxidation and reduction, resulting from an unbalance in nutrients taken into the plant, will show up as an unhealthy symptom. Potassium may be mentioned as an important element affecting the oxidizing and reducing processes. When insufficient potassium is present in a plant, such as corn, iron is made insoluble by excessive oxidation and accumulates in the nodes.

CARBON (C)

Carbon appears in many forms in the physical world: as pure crystalline diamonds, as graphite in "lead" pencils and axle grease, as coal and soot, and as carbon dioxide that gives sparkle and fizz to soda water. In plants, it is a "brick" in the cell walls of tissue, a component of sugar, an atom in the flavor of juices, a part of the structure of color, and even an element in the fragrance of blossoms. In fact, carbon is the keystone of all organic substances. Before life could occur, carbon had to be organized into many of its thousands of combinations with other elements.

Carbon is pulled out of the carbon dioxide of the atmosphere and built into these extraordinary structures by the energy of the sun acting on the green sacks of chlorophyll in the cells of the leaves. This is a master work not yet duplicated by man. Whenever a plant is unable to perform this construction job with carbon because of a shortage of some element necessary to the process, or because of an excess from which an unbalance sometimes results, some symptom of abnormal functioning may appear.

People seldom appreciate that plants must use carbon for their growth in the large amounts listed. The air contains only about 3 one-

hundredths of 1 percent of carbon dioxide; thus, vast volumes of air must be worked over by plants in order to obtain enough carbon in the form of carbon dioxide. In fact, if the air were richer in this substance, plants could grow faster and bigger than they now do. The plants of the coal age grew bigger than modern plants, and some geologists hold to the theory that the atmosphere was richer in carbon dioxide then than now.

NITROGEN (N)

Modern farming practices are generally nitrogen-depleting. When America passed from the Indian to the white man, the storehouse of nitrogen in the organic matter of forest and prairie soils was opened for rapid emptying. In the warm climate of the South the emptying did not take long; in the cooler North it has been a slower process. Crop production today depends largely either on restoring organic matter to the soil in order that, through decay, it may furnish a revolving supply of nitrogen for crops, or, on a supply of nitrogen in the form of fertilizers. Both procedures are necessary for practical reasons.

About 75 million pounds of nitrogen are found in the air above every acre of land and sea, but to most plants it is as useless in this gaseous form as sea water is to a thirsty man. This atmospheric nitrogen must be combined with oxygen, carbon, or hydrogen before it is of any use to growing plants. Some bacteria, such as those in nodules on legume roots, are able to perform this miracle. The chemist too can "fix" atmospheric nitrogen in fertilizer forms. Nature stored nitrogen in forms available to plants in relatively small amounts in the organic matter of virgin soils, but the process was a slow one. Great reliance now must be placed on chemical fertilizers.

Plant roots take up nitrogen in the form of ammonium and nitrate ions in soil water. Inside the cells these ions are converted into amino acids, of which there is a larger number. The amino acids are recombined to form proteins. Any unbalance, whether from insufficiency or excess, in the supply of nutrients will upset this process. Since nitrogen, the most important plant-food element in proteins, is used in such large quantities, a deficiency is very common in plants grown on upland soils.

PHOSPHORUS (P)

The threads (*chromosomes*) in plant cells that are responsible for subdivision and growth contain phosphorus. If the supply is scanty, the rate of cell division is slowed down and the plants remain stunted and

spindling, both roots and tops. The formation of sugar seems to be independent of the phosphorus supply, for a phosphorus-starved plant will continue to form sugar to such an extent that the amount becomes abnormally large. Some plants tend to turn reddish or purplish with increase in sugar content, hence one symptom of phosphorus starvation. This high sugar content generally is associated with a decrease in formation of starch and cellulose from the sugar. Adequate phosphorus is necessary for starch deposition in seeds, grain, tubers, and other storage organs of plants, as well as for converting sugars to cellulose. The formation of cellulose is a part of cell-wall building and cell division; thus, the theory holds fairly well that an adequate amount of phosphorus is required in formation of new cells.

Phosphates, the forms in which plants utilize phosphorus, also are part of certain of the amino acids that form phosphate-bearing proteins. New growth depends on these proteins, as does the formation of seeds. Phosphorus is essential to germination and seedling development. An adequate supply of phosphorus is a prime requirement for starting young plants.

Since most soils have a marked capacity to convert available forms of phosphorus into unavailable forms, behavior of this element in relation to the reaction of soil, and to its clay and organic-matter content, is of tremendous economic importance. This subject is too lengthy to discuss here; the reader may refer to textbooks on soils for details.

Because of loss of phosphorus through the destruction of organic matter by farming practices, through its removal by crops, and through erosion, this element is very generally deficient in soils. A study of phosphorus-deficiency symptoms in his crop plants is likely to reveal to any farmer that the situation is more acute than he has realized.

POTASSIUM (K)

If you stood leaning against the wall of a bank that had a million dollars in its vaults, and you had only one *dime* in your pocket, there would be a total of one million dollars and ten cents within the area occupied by the bank and you. Out of this great sum, however, only the single dime in your pocket would be *available* for your use. A soil may have a total of 40,000 pounds of "potash" (potassium oxide, K_2O) stored with a volume of 1 acre to a depth of 6 inches, but it usually will have only 100 to 600 pounds, more or less, held in such a way as to be immediately available to plants.

No practical device is known that will quickly release the vast store of

unavailable potassium in the soil for the use of plants. In view of the large amount needed, clearly the fertilization of soils by adding available potash is an operation plant growers must practice for abundant and healthy growth.

It seems strange that plants should need so much potassium when, so far as is now known, they do not build it into the structure of any of their parts. A plant will hold its potassium salts from being washed or leached out as long as it is living, but as soon as it is killed by cutting or any other cause, the potassium, no longer held, will be washed out readily, for example, by rain on dried hay or corn shocks. Some potassium salts also will move from the plant back into the soil as the plant matures.

Not much is known about the function of potassium in plants. More is known about what happens to a plant when this element is deficient. From such information, theories are advanced that potassium enhances the plant's ability to resist disease, cold, and other adverse conditions, and that it functions in the processes whereby sugars are made from carbon dioxide and water. In some manner it acts as a condenser in focusing the energy of the sun to a point where these two compounds will combine.

Potassium starvation is so common in most of the important crops that all growers should know its symptoms.

SULFUR (S)

Sulfur is a major plant nutrient that rarely has been in the spotlight. Plants frequently contain more sulfur than phosphorus, calcium, or magnesium, yet we seem to be better acquainted with the latter elements in their effect on crop production. Pass a cabbage field when it is thawing after a killing frost, and the smell of hydrogen sulfide coming from the decomposing leaves will be a potent reminder that sulfur is very much a part of healthy plants.

When yellow sulfur burns, it is converted into sulfur dioxide (SO_2), a gas that has a choking, stinging effect if inhaled by humans, and is useful as a refrigerant in automatic ice boxes. In the soil, sulfur may be oxidized and then combined with basic ions, such as calcium, potassium and ammonium, to form sulfates. Sulfur is useful to plants as sulfates. In plants, some of the sulfur is built into cystine, an amino acid that forms protein.

One of the sulfates is calcium sulfate, or gypsum (also called land plaster or "plaster"). Legend has it that Benjamin Franklin spelled out

the word "gypsum" on the soil of a hillside in Pennsylvania with calcium sulfate and for a time the letters stood out in bold contrast because the plants in them were stimulated in growth. At a later date, according to reports, the word still could be seen, not because the plants were making better growth but because they were making poor growth where the gypsum had been added. Probably the increased plant growth following the application of gypsum exhausted the soil of other plant-food elements, such as potassium and phosphorus, until it was less fertile than if it had not been untreated. Examination of these plants for nutritional-starvation symptoms would have been interesting.

Another common sulfate is ammonium sulfate, a by-product of the steel, coke, and gas industry. It is used as a fertilizer primarily because it contains about 21 percent nitrogen in the ammonia form, but it also contains 25 percent sulfur. Superphosphates made in treating rock phosphate by the sulfuric acid process contain much sulfur in the form of calcium sulfate. Some potash is produced and used as a fertilizer in the form of potassium sulfate. Thus, sulfur has found a free ride back to the soil. The cost usually has been charged to the other plant-food nutrients that acted as carriers.

Rain also returns as much as 10 pounds or more of sulfur per acre to the earth annually. This is picked up by atmospheric moisture from smoke produced by burning fuel that contained some sulfur. In regions where little or no sulfur-containing fuel is burned, sulfur for plant use may be deficient. Decaying organic matter also releases small quantities of sulfur into the air.

Some soils (including those of volcanic origin) formed from rocks containing little or no sulfur, are deficient in this element. Sulfur containing fertilizers or soil amendments are essential for healthy crops on such soils.

Plants that have insufficient sulfur show characteristic symptoms that may resemble those of nitrogen starvation.

MAGNESIUM (Mg)

Ordinarily crops contain more calcium than magnesium. Differences vary with crops and soil composition.

We owe the beauty of a green world of vegetation to magnesium. It is the key element in *chlorophyll* molecules, the green pigment in plants that traps the energy from the sun and makes plant life possible. This pigment starts the chain of events in food and fiber production that begins with green plants and goes on up through animals and man.

Magnesium is credited with being a companion of phosphates; it combines with phosphates so that the latter can be moved to their proper places in the plants in the form of magnesium phosphate compounds. This bond of attraction still has some mystery about it and awaits additional research to be better understood.

CALCIUM (Ca)

The carbon dioxide in the soil solution makes it a potent solvent for calcium compounds; thus, calcium is leached out of the soil as calcium bicarbonate and soil acidity is increased. Large amounts of calcium and sodium have been carried into the oceans. Sea water is salty from the accumulation of sodium salts; it would be milky from the accumulation of calcium salts, if most of the calcium had not been removed from the water and built into the shells of marine animals to be deposited on the ocean bottom. This is an interesting example of how calcium is used by animals to build bony material. In plants, calcium is built into cell walls to form a protective "sieve" for nutrients to seep through in passing into cells. It also acts as a cement between the walls of cells to hold them together.

As the cell processes develop the complex substances in plants, some organic-acid by-products are formed that would be harmful in excessive amounts were it not for the neutralizing effect of calcium. Oxalic acid, for example, is converted to calcium oxalate. Calcium in plants seems to exist in a sensitive balance with magnesium, potassium, and possibly boron. Any upset in this balance, due to an excess or a lack of these elements, results in abnormal performance of plant functions. An apparent excess of calcium in a plant may actually result from a lack of one or more of these other elements, and the remedy may be addition of the deficient element or elements instead of cutting down on calcium. Similarly, an apparent excess of potassium, magnesium, or boron may really be a deficiency of calcium.

IRON (Fe)

Plants need very little iron, yet it is a most essential element. The top 6 inches of the soil may contain 20 tons or more of iron per acre as iron oxide (Fe_2O_3) yet occasionally on iron-rich soils plants starve for lack of this element. In acid soils, iron usually is available to all plants, but in some neutral or alkaline soils it is so insoluble that plants may have difficulty in absorbing enough. Again, where excessive amounts of soluble phosphates are added to the soil, the iron in it may

be made unavailable to plants by being precipitated as insoluble iron phosphate. This may happen in acid as well as in alkaline soils. Iron deficiency is more likely to occur in sandy than in clay soils, because the latter have greater power to fix or "lock up" excessive soluble phosphates.

The chlorosis that develops in plants starved for iron is associated with failure to form chlorophyll, yet iron has not been shown to be built into this pigment. For the present we must accept the fact that iron is associated in some way with the making of chlorophyll.

MANGANESE (Mn), BORON (B), ZINC (Zn), COPPER (Cu), and MOLYBDENUM (Mo)

These elements sometimes have been called the minor elements because they are required by plants only in trace amounts. This does not mean that they are not vital to the well-being of plants, for their need is all that the word "vital" implies. Fortunately, they occur in sufficient quantities in most soils but supplementary applications of one or another of them is of major importance in the growth of some crops on some soils.

A lack of sufficient manganese or boron is most likely to be associated with calcareous or heavily limed soils, and with alkaline soils of the drier regions. When either of these essential elements is lacking, the plant is just as handicapped in performing its normal function as when it is starving for one of the major elements.

Manganese seems to act as a two-handed (double-valence) reception committee, of which zinc and copper also are members, to greet the other nutrient ions as they enter the plant cell and to direct them to their respective positions where they carry out their functions in the plant. Another way to describe this is to say that these minor elements act as catalysts. Manganese is most likely to be deficient in dry regions, and may be present in toxic amounts in strongly acid soils.

Boron seems closely related to some function that calcium performs in the plant. Whenever the proportion of calcium to boron becomes unbalanced because of a a deficiency of boron, the terminal growing tips of plants fail to develop properly and other characteristic boron-starvation symptoms become evident. If this calcium-boron balance becomes upset because of a shortage of calcium or an excess of boron, a different type of injury to the plant is likely to result. Thus both a deficiency and an excess of boron produce characteristic symptoms. Boron deficiency occurs on alkaline soils of dry regions and also on calcareous (lime) soils of humid regions.

Zinc is required by all plants for normal growth, but the amount needed is very small, about one-one hundredth as much as the amount of phosphorus. In alkaline soils, such as those occurring in regions of limited rainfall, the amount of available zinc may be so low that sensitive crop plants suffer. Such plants as corn, beans, sorghums, cotton, tomatoes, and potatoes may be badly stunted unless zinc sulfate is provided in amounts of about 1 pound per acre. Zinc has been found to be effective in treating some physiological diseases, but not much is known about its action in plants. Zinc also has been found a necessary additive to certain soils, especially those of the Gulf Coast States and California.

Copper in sufficient quantities to supply plant needs has not been found lacking in upland soils that are low in organic matter. Need for copper appears to be associated with high organic-matter content soils, particularly peat soils that are alkaline and contain appreciable quantities of ferrous iron.

Molybdenum is the element most recently discovered to be essential to plant growth. Very small amounts are needed; 1 to 4 pounds per acre in the form of sodium or ammonium molybdate is adequate. Molybdenum compounds are unavailable on acid soils. However, some neutral or alkaline soils may be so low in molybdenum that plants grown on them are deficient. Nodule bacteria of legumes are dependent on molybdenum, and a deficiency causes legume plants to become light green which is typical of nitrogen starvation.

An important point regarding these trace elements, and perhaps others, is that if present in quantities larger than plant needs they are likely to be toxic or poisonous, yet actual quantities still may be small. Excessive as well as deficient amounts produce characteristic symptoms.

ENVIRONMENTAL FACTORS INDUCING SYMPTOMS

Plants are things that have taken a long time to develop. They are complex systems of life that have evolved slowly from more simple forms. In Nature's laboratory, plants have had to adapt themselves to competition from other species, as well as to fit in with a lot of external forces, such as variations in soil, temperature, light, and disease. Through breeding, man has intensified certain aspects of plants, but basically they will grow at an ideal rate only when every external factor is most favorable. This is the ideal for which we strive, because any departure from it affects our economic interests. Therefore, we are concerned not only with shortages or excesses of the vital plant-nutrient elements but also

with any other factors affecting plant growth. Let us consider some of the factors which contribute to the environments of plants.

ROOT ZONES

The soil is the storehouse that dishes out water, minerals, and nitrogen to plants through their roots. Unfortunately plant roots have to grow into this storehouse to pick up the mineral nutrients as if they were on shelves. In other words, these mineral nutrients do not move much in the soil solution; only nitrogen as nitrates can move freely in soil waters. Therefore, the physical condition of a soil is such that plant roots cannot travel everywhere in it freely, real starvation can result although it may be well stocked with nutrient elements. So do not overlook the importance of soil structure and drainage when diagnosing plant nutrient needs.

Nature's way of meeting the requirements of ideal soil tilth was to let organic matter accumulate. Much of man's trouble with his plants has resulted from use of too many practices that destroy soil organic matter. The surest way to efficient plant feeding is to return a lot of vegetable matter to the soil. That will open all the feeding trails to the roots, and the organic matter in itself is food for healthy and friendly microorganisms that bring insoluble plant nutrients into solution and keep some root diseases in check. Organic matter also improves soil structure in such a way that the available supply of water in soils is greatly increased. There is more magic to organic matter than science has yet shown.

TEMPERATURES

Every farmer knows that spring growth is poor until the soil warms up. This is due in part to the fact that little or no available nitrogen can be made from the proteins in soil organic matter until the soil is warm and full of free oxygen brought into the soil by warm spring rains. Regardless of type or organic-matter content of unnitrated soils, in cool humid climates grasses and grains starve for nitrogen until the soil becomes warm. Thus, nitrogen starvation usually occurs as the first limiting nutrient factor to plant growth over wide areas, even though later in the season nitrogen may become adequate while other factors become limiting.

Air temperatures also have profound effects on plant performance. On the one hand, plants make carbohydrates through photosynthesis,

while on the other hand, respiration or the burning of sugar goes on both night and day. If temperatures are too high, especially at night when photosynthesis is stopped, so much sugar can be lost as to affect growth, and especially yields of starch crops. In a certain corn field planted too thick for adequate light at the University of Illinois, the rate of respiration in the extremely hot weather of August 1947 was so high that all the lower leaves died for lack of carbohydrates. The symptom definitely was that of carbohydrate starvation, but looked somewhat like that of nitrogen hunger.

OVERLIMING ACID SOILS

Since the solubility of such elements as iron, zinc, manganese, and boron is reduced when the pH value of the soil goes above the neutral point (pH 7.0), grave danger of inducing real starvation for these elements lies in liming the soil in excess of actual needs. Overliming of sandy soils is easy, because they need much less lime than clay or high organic soils of the same pH.

Overliming may upset the balance of magnesium or potassium inside plants. If one of these nutrients gets into plants in too large a dose it cuts down the function of the other and trouble may result from the unbalanced condition. The safe guide is to stay below pH 7.0 when liming.

INSECTS, DISEASES, AND MECHANICAL INJURY

Do not mistake the work of leaf hoppers on alfalfa for potash or boron starvation. Insects that feed on roots, may cause hunger signs of various sorts on a variety of crops. Likewise, alfalfa wilt may hurt the plants in such a way that potash starvation symptoms develop. Various corn or grain diseases give symptoms that look somewhat like hunger signs, but close study reveals differences.

The purple color of older corn plants should not be mistaken for phosphorus starvation. Any condition in the corn plant, and to a lesser extent in other members of the grass family, that causes sugar concentrations to accumulate abnormally will result in the development of purple or reddish purple pigments. Barren corn stalks having no ears for the storage of sugar are a good example. Leaves that have been broken or partially cut so that the sugars cannot get out are another.

WHEN DOES SOIL STARVATION START?

Man has become accustomed to certain magnitudes of crop yields that may be merely results of limitations imposed by nature. For example, nitrogen starvation that occurs on high-organic-content soils in cool spring weather limits total yields. Man with his scientific knowledge is not satisfied with this limitation, so he sets out to correct a condition that in the past he has accepted as unavoidable. We have accepted that plants grow to a certain size when all soil nutrients are adequately supplied, when in fact they may be starving for carbon dioxide or even sunlight. So we see that starvation is a relative term. Acceptance of some starving may be necessary since we may not be able to correct it economically but unfortunately we frequently accept starvation conditions that can be readily corrected.

Starvation symptoms usually appear long after hunger actually begins. Much damage to growth and yield usually has occurred when a specific symptom shows up. Why then read hunger signs? Because they give us knowledge of what the troubles are so that in many cases we can correct them at once, and in all cases we can alter treatments for next year's crops so as to correct handicaps.

"Hidden hunger" is the term sometimes used to describe a condition where deficiency symptoms are not visible but plants are not thriving as they should because the amounts of available essential nutrients will not support greater growth. Hidden hunger may greatly reduce yields, and also the quality of crops without the plants showing deficiency symptoms. For example, the difference between 75 and 125 bushels of corn per acre, between 300 and 500 pounds of cotton lint, or between ordinary fruit and fruit of high flavor and keeping quality may be the difference between apparently normal crop plants that are actually suffering from hidden hunger and others which are truly well-fed. Supplementation of supplies of nutrients in soils with suitable fertilizers, in sufficient amounts to fully meet needs for plant growth has become the standard method of increasing yields and quality of crops. It not only corrects hunger signs but also corrects hidden hunger for essential nutrients.

TESTING PLANT TISSUES TO DETERMINE NUTRIENT STATUS

Since plants may have inadequate contents of one or more nutrients while deficiency symptoms are uncertain or undetected, chemical tests of leaves or leaf stalks (petioles) to determine needs for nutrient

supplements are useful. Leaves or petioles selected for testing come from young, fully developed leaves that are actively functioning in plant metabolism. By comparing results of chemical tests of leaves on plants being tested with standards developed from healthy productive plants, these plant tissue tests reveal any deficiencies present. Certain tissue tests have been simplified to the point that they may be easily taken to the field for testing plants in different areas and in different stages of development. Such field tests should be supplemented by more precise laboratory tests, particularly where the content of any essential element appears to be deficient or in such excess as likely to become toxic. These tests are particularly useful on fruit trees and on vine and cane fruits. However, they are applicable to nearly all crops, as a means of supplementing visual hunger signs; thus they serve as guides to practices that insure optimum nutrient supplies.

SOIL ACIDITY AND ALKALINITY

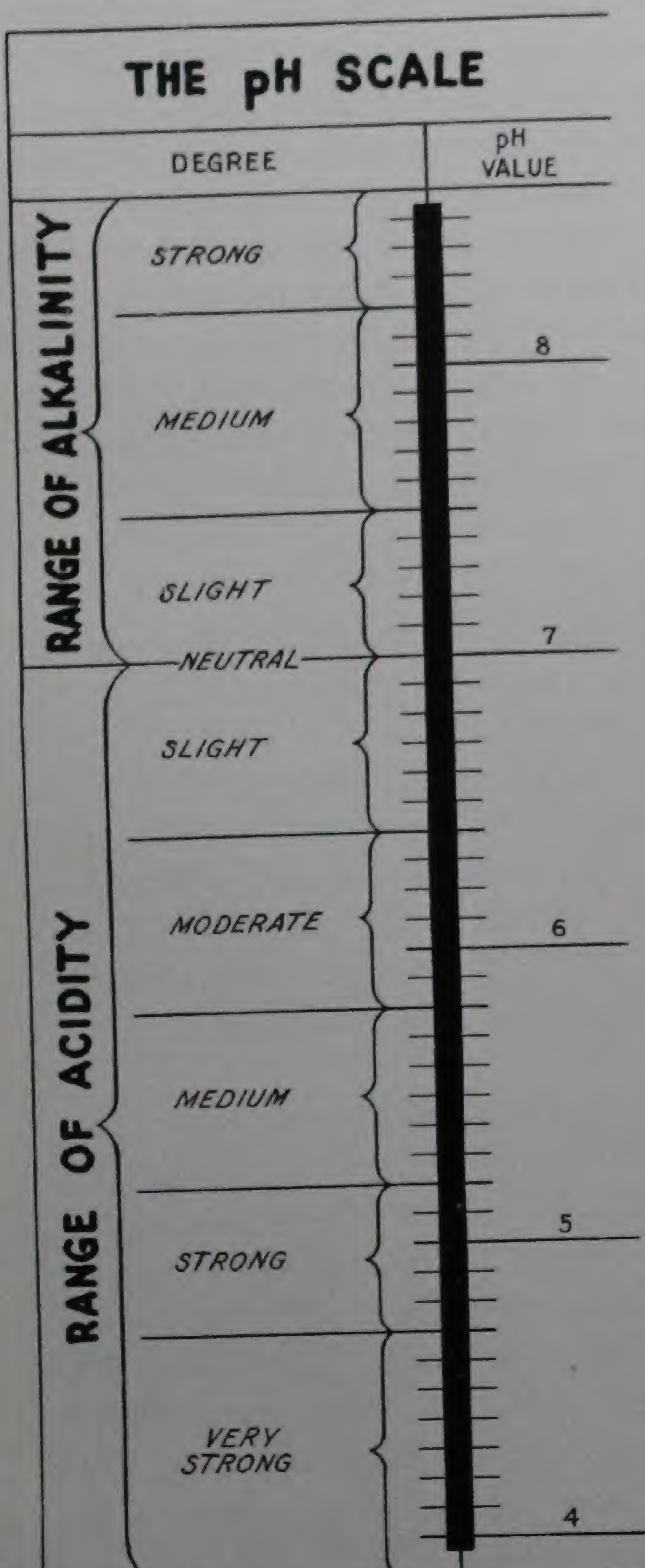
Soil acidity is mentioned here because it greatly affects the behavior and availability of most plant nutrients. Growers of crops should understand what soil acidity is and how it is measured.

The principal acid in soils is not hydrochloric, nitric, or any other of the common drug-store acids. Such acids are soluble, easily wash out of the soil, and do not accumulate. However, acidity is known to increase with prolonged movement of rain water through the soil. This comes about because the main soil acids are themselves the colloidal particles of clay. They are insoluble and accumulate as soil weathering processes progress.

Clays do not wash out of soils by leaching, but the alkaline ions of calcium, magnesium, potassium, and sodium that were fastened (adsorbed) to the surfaces of clay particles in the virgin state become loosened and wash out of the soil. When clay particles are saturated with a mixture of calcium, magnesium, potassium, and sodium ions, the soil has no acidity and is alkaline, some say, "sweet" (the term "sweet" is incorrect and should not be used). When these alkaline nutrient elements are leached out they are replaced by hydrogen, the acid element (H) of soil carbonic acid ($H_2O + CO_2 = H_2CO_3$, carbonic acid). This hydrogen is absorbed to the spots on the clays from which these alkaline elements have been removed with the result that the clay becomes a hydrogen clay and the soil becomes acidic.

Other soil acids occur, such as organic acids produced by decom-

posing vegetable matter, but the clay acid is dominant in acid soils. Since clays in soils carry the principal acids, a heavy soil with a great deal of clay has more acidity to be neutralized by liming than a sandy soil with only a small amount of clay in it.



Courtesy of National Lime Association

Figure 1. The pH scale, showing the ranges of acidity and alkalinity at which crop plants grow.

The strength (intensity) of acids is stated somewhat like the size or gauge of wire, in which the smaller the number in the scale the heavier the wire. The range of soil acidity is called the pH scale (figure 1). Here too the smaller the pH value the stronger the acid. Thus, a pH of 4.0 is about the extreme acidity for any soil. A pH of 7.0 is neutral, and above pH 7.0 a soil is alkaline and may contain free lime.

Its pH value indicates the intensity or strength of an acid but tells nothing of the amount or quantity that may be present. Let us consider vinegar, a weak acid in common use. It has a pH of about 2.0 whether you have a quart or a gallon, but it will take 4 times as much limestone to neutralize a gallon as it will take to neutralize a quart. In a similar way, soils may have the same pH value and still differ greatly in lime requirements. A sandy loam with a clay content of 12 percent would not require much lime to change its acidity from pH 5.0 to 6.5, but a clay loam with a clay content of 24 percent would require about twice as much lime to produce the same change in pH.

Few crop plants will grow be-

low pH 3.5 or above pH 9.0. The most favorable pH range for most crop plants is from 6.5 to 7.5.

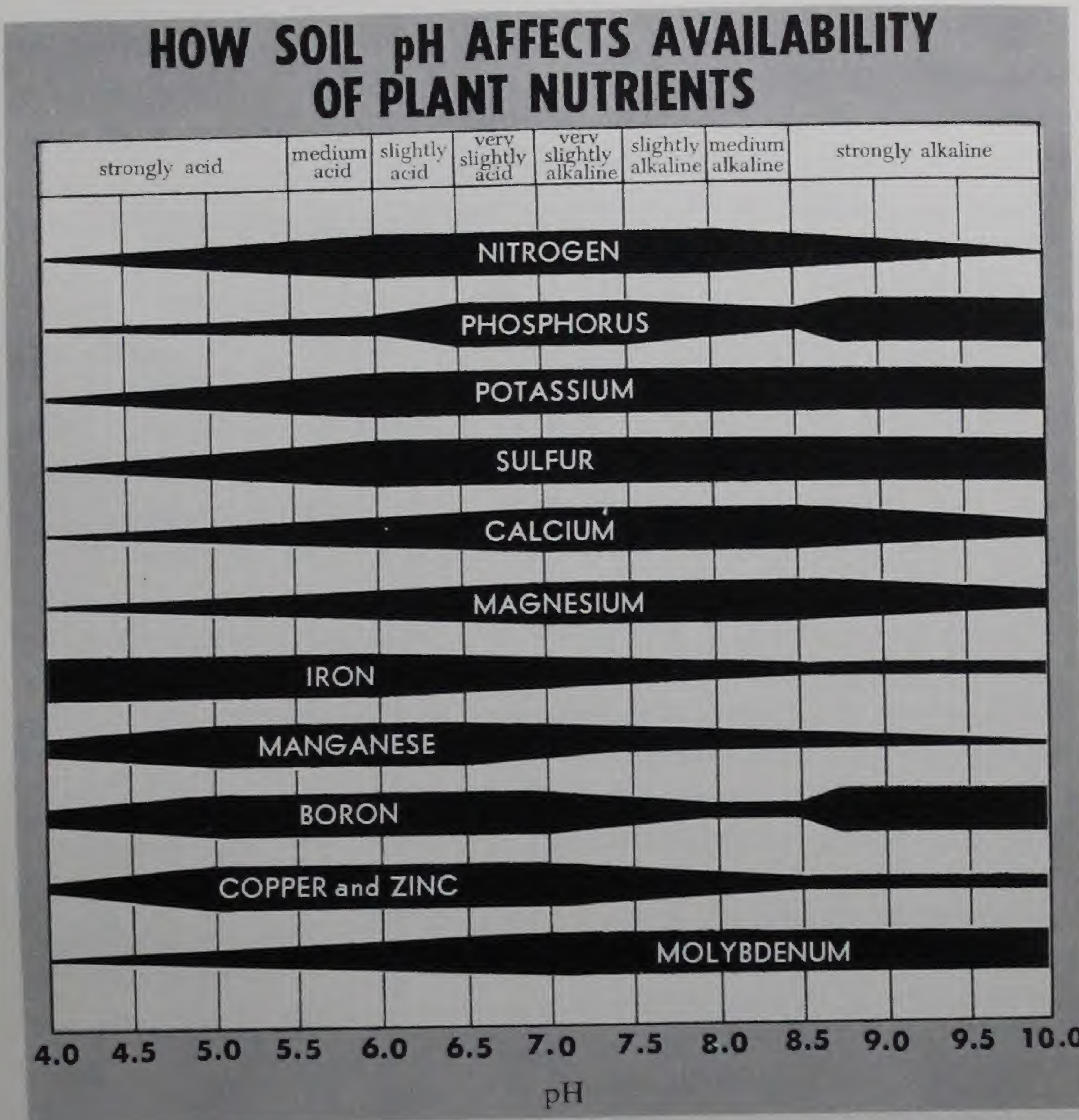
SOIL ALKALINITY

Soils in semiarid and arid regions often have a pH above neutral, and pH values above 8 frequently cause malnutrition in plants. When evaporation is high and rainfall is low, soluble salts tend to accumulate, a condition which produces high alkalinity. Irrigation may increase this tendency for soluble salts to accumulate in the soil and on the surface, particularly if internal drainage is inadequate. These salts, called alkali, provide an excess of sodium, calcium, magnesium, and potassium in combination with chlorides, sulfates, carbonates, and bi-carbonates which often become toxic to plants. When sodium carbonates and bi-carbonates accumulate to the point where a pH of 8.5 or above is produced, the soil organic matter tends to dissolve and produce "black alkali" which is highly toxic to plants. Establishment of internal soil drainage, and treatment with gypsum or sulfur, aids in reduction of black alkali.

The soil reaction (acid-neutral-alkaline) has a pronounced effect on the availability of plant nutrients present in soil. The general influence of soil reaction on the availability of plant nutrients has been summarized by Truog, as shown in figure 2. The width of the bar indicates degree of availability. A pH of 6.5 to 7.5 provides the best general status as to availability of essential nutrients in the soil. (E. Truog. Soil Science Proceedings 11:305-308. 1946)

SOIL ACIDITY

Strongly acid soils not only reduce availability of phosphorus, potassium, sulfur, calcium, magnesium, but such soils may contain so much soluble aluminum and manganese that plants may be injured. Aluminum is not an essential element, but it is generally present in soils, and becomes soluble as acidity increases. Soluble aluminum is directly harmful to plant roots, and indirectly harmful because it precipitates phosphorus and creates a deficiency of that element. Manganese is required by plants in very small amounts, but when present in larger quantities it may be toxic. Liming to raise the pH of acid soils to 6.0 or above will prevent aluminum and manganese toxicity.



Courtesy of National Plant Food Institute

Figure 2. Effects of soil reaction on availability to plants of soil nutrients (after Truog). The width of the bar determines the relative availability of each element with a change in soil reaction.

WHY READ THE HUNGER SIGNS?

Information about the functions of the various nutrient elements in plants has been obtained by scientists largely through carefully conducted experiments in fields, greenhouses, and laboratories.

Most intensive studies of the fundamental nature of plant nutrition have been made in greenhouses, with soils in pot tests and with nutrient-solution cultures, in which the plants were grown directly in solutions or on sand or gravel to which nutrient solutions had been

added. Field experiments have been used chiefly for testing the practical and economic aspects of fertilizers.

CORRECTING "HUNGER SIGNS"

By the time plant symptoms of a nutrient deficiency are clearly identified, much damage to the crop often has occurred. However, prompt treatment may produce remarkable results. Spraying crop leaves with dilute solutions of compounds bearing the deficient element is the most rapid corrective measure. Wherever very small amounts are needed, as of the "trace" elements, iron, manganese, boron, zinc, copper, and molybdenum, such sprays may largely correct deficiencies in current crops. The more promptly the appropriate element is applied, the less will be the damage, and the more effective the response. In recent years, use of "chelated" compounds of these trace elements has increased since the chelates are more readily absorbed by plant leaves. Obviously, determination of the specific element needed and the concentration of spray to produce results without burning the leaves is important.

Amounts needed of the major elements, nitrogen, potassium, calcium, magnesium, and sulfur, usually are greater than may be effectively supplied as leaf sprays. In the case of cultivated crops, supplemental feeding may be done by application of solid or liquid fertilizers as side dressings with a cultivator as soon as the deficiency is identified. Such treatments are less effective on orchards or other perennials because of the time needed for compounds to enter the soil, to be absorbed by roots, and to be transported through the plants.

Nutrient needs of crops may be met by use of dry, solid fertilizers to supplement supplies already in soils and meet the needs of the crop being grown. Although solid fertilizers are widely used, liquid fertilizers also are feasible. The earlier forms of liquid fertilizers were carriers of nitrogen, but complete liquid fertilizers, carrying nitrogen, phosphorus, and potash, are now becoming common. Accurate application of liquid fertilizers requires special equipment, but the effectiveness of fertilizers applied as liquids is generally equal to that of solid fertilizers.

SOIL TESTING FOR PREDICTING NUTRIENT NEEDS

Rapid soil testing is in wide use to determine the status of soils before crops are planted, and during the growth of perennials. A

soil sample representative of that in a field is exceedingly important if reliance is to be placed on the results of its analysis. Directions for obtaining such samples are provided by laboratories set up to make quick soil tests and to interpret results. Testing usually begins by determination of soil reaction (degree of acidity or alkalinity), and of lime requirement for correcting acidity when present. The nitrogen supplying power of a soil is not determined directly but is inferred from its organic matter content, its pH, its texture and structure, and the crops previously grown, plus any animal manures that have been applied recently. However, rapid soil tests will reveal current supplies of phosphorus and potassium, expressed as very low, low, medium, high, or very high. Tests also may be made for calcium and magnesium, and the relative amounts of these in relation to each other and to potassium often are important. Contents of essential "trace" elements may be determined spectroscopically, but these methods are complex; resort to such tests often is limited to soils on which deficiencies in these elements are strongly suspected.

Interpretation of quick soil tests requires an understanding of the characteristics of the kind of soil being tested, the temperatures and moisture supply expected during the growing season, and the specific nutrient requirements of the crop to be grown. Obviously, success in making recommendations based on chemical soil tests depends on actual field trials that have been made to determine just what each level of supply indicates as to the amount of lime, fertilizer, or soil amendment that should be applied for best plant growth. Established laboratories have a rich background of experience for this kind of interpretation.

Whenever hunger signs develop on plants growing in fields where soil tests have been made, the test results are exceedingly useful in identifying the related status of other nutrients. Causes of hunger signs often are more complex than a deficiency of a single element.

FERTILE SOIL CUTS COST OF FARMING

Hardly any farm lands exist in the well developed regions of the world where native soil fertility will produce crop yields sufficient to make production profitable. Agricultural soils usually must receive fertilizers to increase nutrient supplies, and in humid regions lime to correct soil acidity. Production of harvested crops and of animals on grazing lands at profitable levels is dependent on maintenance of soil

productivity through wise management of the land by its operators.

Although use of fertilizers is now nearly universal in humid and irrigated regions, a great many farms still are being operated at such low soil fertility levels that production is limited to the point of little or no net income. Any system of cropping or grazing removes substantial amounts of nutrients from the soil each year. Unless these withdrawals are restored by application of fertilizers, crop and pasture

Courtesy of R. E. Hodgson, Animal Husbandry Research Division, U.S. Dept. of Agri.

Figure 3. Cow showing severe deficiency of phosphorus. This cow subsisted on low-phosphorus forage on a Texas ranch where the soil phosphorus is very low. On such land, phosphate supplements are required for normal growth of livestock.

growth will decline. In addition, nutrient supplies of soils must be raised to the point where plant growth can make full use of the free sunlight, rain, and warmth.

One basic principle of good farm management is that net profits generally increase with higher per acre yields, particularly when higher yields are the result of supplying nutrients in such amounts and ratios as to fully meet the growth capacities of the crops grown.

Thus, when corn yields are limited to 50 bushels per acre by low fertility, the value of a harvested crop may barely equal its total cost of production, a 75-bushel yield may provide a modest net profit, while

100 bushels will assure even higher net returns. The same principle applies to small grains, to cotton, to silage, to hay, and to pasture. Higher per acre yields are necessary for substantial net profits. The costs of light, rain, and warmth are negligible; and maintaining higher soil fertility to capitalize on nature's free gifts brings rewards for good soil and crop management.

How to set up and maintain a profitable production program now is well understood. First, the total nutrient requirements of each crop for higher yields is known. Calculation of total nutrient supplies needed for the higher crop yields desired, such as 100 bushels of corn, or 4 tons of hay, is relatively simple. Second, rapid chemical soil testing reveals the nutrient supplying power of the soil. Third, the contributions of manure applications and of sod plowed under, are readily estimated. Fourth, the difference between the crop's requirements and the amounts of each nutrient supplied by manure or sod, plus that left in soil from the previous crop, must be provided as fertilizers.

Technical Bulletin 262 by R. B. Becker, Wm. Neal & A. L. Shealy

Figure 4. This cow had both hips "knocked down" (broken) during the period on low-calcium rations. Milk yield is restricted after skeletal calcium is reduced. Forages consumed were unfertilized pasture grasses growing on acid sandy soil, and corn and sorghum silages from lightly fertilized deep Norfolk sand.

Courtesy of Florida Agricultural Experiment Station

Figures 5 and 6. Above: an example of nutritional anemia. Right: the same calf after receiving iron-copper supplement and bonemeal. While only a trace of copper is needed by plants it is now known that animals also need this trace.

Satisfying the full nutrient requirement of each crop is the gateway to higher per acre yields and higher per acre profits. Fertile soil cuts the cost of producing each bushel, ton, or unit of feed, and thereby increases total net farm profits.

RELATIONSHIP BETWEEN PLANT AND ANIMAL NUTRITION

All animals, including man, are dependent, directly or indirectly, upon plants for their food. Animals fed on mineral-deficient plants are poor themselves and the products that they furnish are of low quality.

Cows which graze on lands deficient in phosphorus, for example, lack an essential element, an element they need for healthy bones. The early symptoms are hard to see, but the later stages are plain enough. (Figure 3.)

Cobalt is not known to be needed by plants, but animals produced on feed deficient in cobalt are weak, and they have rough coats and poor muscular coordination. (Figures 7 and 8.)

Iodine is another element needed by animals but not known to be needed by plants. However, since most minerals are needed by both plants and animals, the problem of plant and animal nutrition resolves itself into one of simply growing healthy crops.

Courtesy of Florida Agricultural Experiment Station

Figure 7. A milk cow suffering from cobalt deficiency. Emaciation is due to lack of appetite for grain and roughage. Cobalt is not known to be needed by plants, but plants need to contain it to supply the needs of animals.

Courtesy of Dr. C. F. Huffman, Michigan State College

Figure 8. The same cow as in figure 7, 16 days after starting cobalt feeding.

Chapter II

Nutrient Deficiencies in Corn, Sorghums, and Small Grains

By B. A. Krantz and S. W. Melsted *

SOMEONE has said, if starved plants could only squeal like hungry pigs, we would pay more attention to their fertilizer needs.

Fields of healthy, vigorous plants indicate high soil fertility. However, when the available supply of any one of the essential mineral elements becomes exhausted, growth is seriously impeded. The symptoms of a deficiency may be regarded as the language plants use to indicate the nature of their distress (figure 1). In some cases these symptoms afford a better understanding of the nutrient relationships between soil and plant than can be obtained from detailed chemical analyses of the soil. Whenever possible, dominant symptoms of nutrient deficiencies in crops should be translated into plans for corrective practices in soil management.

Visual symptoms of nutrient deficiencies are difficult to interpret under field conditions because environmental factors constantly affect the plant. Prolonged periods of adverse growing weather may harm corn or sorghum plants. Severe winters may adversely affect winter grains. Insect and fungus disease may attack the leaves of plants and cause damage marks difficult to distinguish from deficiency symptoms. Plants already weakened by malnutrition often are more severely attacked by disease and insects, or damaged by unfavorable weather, making positive identification of symptoms more difficult. For these reasons, detailed study of typical deficiency symptoms in plants under actual known, or controlled, conditions is necessary.

Some crop plants are better indicators of nutrient deficiencies than others. Corn and sorghum plants with their wide expanse of broad leaves

* B. A. Krantz is Extension Soils Specialist, University of California, Agricultural Extension Service, and S. W. Melsted is Professor of Agronomy, University of Illinois. G. N. Hoffer, American Potash Institute, Inc., was senior author of a similar chapter in the previous editions of "Hunger Signs."

are better indicators of changes in the supply of available nutrients than are small grain plants with their narrow leaves. Thus, corn plants in rotation with other crops serve as excellent indicators of the fertility of the fields in which they are growing. This is especially true for nitrogen, potash and zinc.

Although small grains in the rotation also may show signs of nutrient deficiencies, their symptoms are, as a general rule, less striking and more

Figure 1. Learning the language of hungry corn plants is first aid in correcting your soil fertility problems.

difficult to interpret than those for corn or sorghum. Late spring frosts, prolonged wet periods, or insect invasions often have damaging effects on the small grain plants and make it difficult to diagnose the disturbance as definitely due to malnutrition. For these reasons the symptoms shown by corn and sorghum plants will be discussed at length while those of the small grains will receive only general attention.

Experience shows that the use of simple semi-quantitative chemical tests for the detection of nitrogen, phosphorus, potassium, or magnesium compounds in plant tissue can be a valuable aid in diagnosing nutrient deficiencies. When well nourished and in good health, plants carry

reserves of these substances in their tissues during the active growing season, and the presence of such reserves is indicated by tissue tests. When the reserves of any of these nutrients become exhausted, the tissue tests are negative and confirm the symptoms indicating deficiency; therefore, these chemical tests can become invaluable for use in the field when other complicating factors are involved. These tests can be used at any time during the growing season.

Practical field experience, both in observing plants grown under known field conditions and in testing plants, is the best background training for the diagnosis of deficiency symptoms. Such experience, coupled with a good knowledge of the growth characteristics of the crop observed usually results in accurate diagnosis of the nutrient deficiency.

NITROGEN (N) DEFICIENCY

Nitrogen is the most universally deficient nutrient in nonleguminous plants. Corn, sorghums, and small grains are very sensitive to nitrogen supply and exhibit an easily recognizable deficiency symptom. Since these crops are grown all over the world, they provide a valuable indicator with which to identify nitrogen deficiency. Since nitrogen is deficient in most mineral soils, nitrogen fertilization and management is a key factor in food and feed production. Therefore, it is important that symptoms of nitrogen deficiency be recognized by agricultural advisors and growers throughout the world.

Nitrogen enters into the composition of many organic compounds in the plant. As an essential element in protein, it is needed for the growth and development of all living tissues. Nitrogen is an important constituent of chlorophyll, the green pigment of healthy leaves. A deficiency of nitrogen limits chlorophyll development and the yellow pigments become more prominent. Thus, the plant turns lighter green or yellow, depending upon the intensity of the nitrogen deficiency.

The corn plant uses more nitrogen than any other fertilizer element. Nitrogen is needed by the corn plant throughout the growing season, but it is used in greatest quantity during the period of most rapid growth which extends from about 2 weeks before, to 3 weeks after tasseling. Sayre (37) found that daily uptake reached 4 pounds per acre and that about half the total nitrogen requirement was absorbed during this 5-week period. The nitrogen contained in a 125 bushel corn crop (3.5 tons) varies greatly with soil fertility and variety grown, but averages about 160 pounds per acre. The corn plant is very sensitive to nitrogen

supply, and nitrogen fertilization, when needed, gives large yield increases. For example, in a North Carolina experiment, the no-nitrogen plot yielded 9.2 bushels while the 180-pound nitrogen plot produced 128.6 bushels (24).

Raheja and Krantz (35) found that nitrogen uptake by sorghums was very rapid during the fourth to the eighth week when the daily uptake was as high as 4 pounds per acre. The total nitrogen requirement for sorghum, however, was somewhat less than that of corn.

Small grains are likewise responsive to nitrogen applications but their total requirements are considerably less than that of corn. Excessive amounts of nitrogen often cause lodging in small grains which may be accompanied by a reduction in yields. Therefore, fertilization programs should be adjusted to provide adequate but not excessive rates of nitrogen application to small grains.

Plant tissue tests provide a quick means of confirmation of nitrogen deficiency (see plate 14). Both the Bray Test (6) and the diphenylamine test (25, 41) are simple rapid tests which can be used in the field. When greater precision is desired, we suggest total nitrogen analysis of the sixth leaf at silking as described by Tyner (40).

Symptoms: In young corn plants, nitrogen deficiency is characterized by stunted and spindly growth and yellowish-green foliage.

When nitrogen deficiency occurs later in the growth of corn plants, a definite leaf symptom develops due to the translocation of nitrogen from the older to the younger tissue. This shows up as yellowing since the yellow pigments in the leaves, such as the carotins and xanthophylls, predominate after the loss of the green chlorophyll pigment takes place (12). The tips of the lower leaves are the first to show this yellowing. If the nitrogen deficiency persists, the yellowing will follow up the leaf midribs in a typical V-shaped pattern, the leaf margins remaining green as is shown in plate 1A and 4B. In some cases the symptom shows up merely as a general yellowing of the lower leaves. The pattern of the symptom depends upon the rate at which the deficiency develops. A few days after the leaf tissue turns yellow, it dies and dries up as is shown on the three lower leaves in plate 1A. The dying of the lower leaves frequently is referred to as "firing," and may occur under either moist or drought conditions. A field view of firing is shown on the right side of plate 2. Although nitrogen deficiency is by far the most common cause of firing, other conditions, such as extremely dry or hot weather, also can bring about death of leaf tissue. After the leaves are

dead, it is difficult to diagnose the cause. An example of firing due to drought is shown in plate 1B. An important difference between this and nitrogen firing is that it occurred on the upper as well as lower leaves of the plants. The plants shown in plate 1B were adequately fertilized.

If plants are observed during the early development of the symptom, it is easy to distinguish between nitrogen deficiency and dry weather effects. Figure 2 shows typical leaf roll associated with soil moisture deficiency.

If the soil supply of nitrogen is relatively low, a mild drought may accentuate nitrogen deficiency. Drought can influence nitrates in two ways: first, during dry spells nitrates move up in the soil layer and out of the actively feeding root zone (26); and second, as the top soil dries out the zone of nutrient absorption by roots becomes restricted.

Figure 2. Soil moisture deficiency affects entire plants. The leaves curl upward, wilt, and become very dry.

In sorghums, nitrogen deficiency symptoms are similar to those of corn. In young small grain plants, nitrogen deficiency is characterized by stunted spindly growth and yellowish-green foliage, plates 12A and 13B. As the plants become older, interpretation of the symptoms become more difficult because of confusion with symptoms of diseases and other causes.

PHOSPHORUS (P) DEFICIENCY

All plant cells contain phosphorus compounds. Phosphorus is necessary for cell division, in growing root and shoot tissue, and in developing seeds and kernels of grain. It is essential for all phases of plant development.

Symptoms: Phosphorus deficiencies in corn, sorghum, and small grains are somewhat similar. Mild deficiencies usually are characterized by stunted growth but by no very clear-cut leaf symptoms; more severe deficiencies usually cause purpling or browning of the leaves, starting

with the older growth and working up the plant and from the tips of the leaves inward. Eventually leaf tips start to die and turn dark brown. In corn and sorghum the purpling is quite striking (plate 3). In the small grains, and in some inbred lines of both corn and sorghum, the purple color is absent, but the dull browning of leaf tips and eventual death of tissue are quite pronounced, as shown in plate 12B for oats and 13C for wheat.

For most commercial varieties of corn, the purple color is a valid

Figure 3. Ears produced on slowly growing, phosphorus-deficient plants are often imperfectly pollinated because of the delayed emergence of the silks. Dropped rows of kernels result.

symptom of phosphorus deficiency. The purple color develops as sugars accumulate and the anthocyanin pigments increase (12). As the symptom develops the plant loses its chlorophyll, allowing the purple pigment to dominate the leaf color. However, not all varieties of corn and sorghum carry the genetic factors for the purple pigment and, in such cases, a phosphorus deficiency is indicated by a bronze coloration of the same pattern as that developed in plants with the purple pigment.

Phosphorus deficiency symptoms are most pronounced in young plants, which usually have a greater demand for this element than more mature plants. A soil capable of supplying the phosphorus needs of young plants will seldom become phosphorus deficient later in the season;

therefore, all crops should be examined for phosphorus deficiency during the early stages of growth. Similarly, a young plant showing severe phosphorus deficiency seldom will "grow out" of the deficiency and the symptoms will persist to maturity. Phosphorus starvation tends to delay maturity. In corn, this is particularly noticeable during pollination when silking may not occur until most of the pollen has been shed, resulting in imperfect ear formation (figure 3). The usual symptoms of phosphorus deficiency in corn ears are irregular kernel rows, a twisted look of the ear, and imperfectly developed ear tips.

Plants show deficiency symptoms only when severely starved for a particular nutrient. Profitable crop responses to fertilizer use often may be obtained from applications to soils on which the untreated crop shows no visual symptoms of nutrient deficiency. To determine when the crop is "hungry" but shows no symptoms of "starvation," tissue tests (25, 40) can be a useful diagnostic tool. Generally, for corn, sorghum, and small grains, if tissue tests show very low levels of soluble phosphates in the plant sap the crop will respond to phosphorus applications.

POTASSIUM (K) DEFICIENCY

Potassium in plants is associated with protein activity, primarily in the maintenance of a positive ion balance to satisfy negative ion charges on the protein. Ions are groups of atoms that tend to operate as units which carry either positive or negative charges. The balanced condition of positively charged ions with those negatively charged produces a stabilized compound.

So far as is known, potassium is not a constituent part of any of the structural tissues of plants, although its absence often causes a loss in straw stiffness and lodging of crops. Potassium moves readily from one plant part to another, therefore leaf symptoms appear on the older leaves first, as the younger actively growing leaves draw potassium away from them (18).

Potassium is needed in large quantities by most plants for normal growth. Potassium ions usually dominate the various salts found in plant sap. Mature plants require about the same level of potassium as younger plants, therefore symptoms will occur as frequently during early growth as at any other stage of development. If the soil does not supply sufficient potassium for the seedling stage, plants seldom will "outgrow" the deficiency during later development.

Symptoms: The first symptoms of potassium deficiency are a shorten-

ing of the internodes (plates 5 and 6) and a dwarfing of the plants, with a general loss of the dark green color indicative of healthy growth. A more severe deficiency usually produces a bronze to yellow discoloration along the edges of the older lower leaves. In corn, (plate 4C) and sorghum, the marginal discoloration is continuous from the tip to the base of the leaf (plate 1C) while in small grains it is a general mottling, as in the case of barley (plate 12D), or bronzing of the leaf tip as in the case of wheat (plate 13D). In the small grains, potassium deficiency symptoms are extremely difficult to diagnose by visual means and always should be supported by tissue tests. In severe cases, the marginal discolored areas on corn and sorghum, and leaf tips on small grains, become dry and scorched, giving a very ragged appearance to the leaves. Eventually the leaf edges and tip tissues die, leaving small areas at the bases and midribs alive and green, as shown in plate 1C for corn.

Potassium deficiency symptoms are sometimes reflected in the corn ear. Usually the ears are small and tend to have very pointed, poorly developed tips (figure 4).

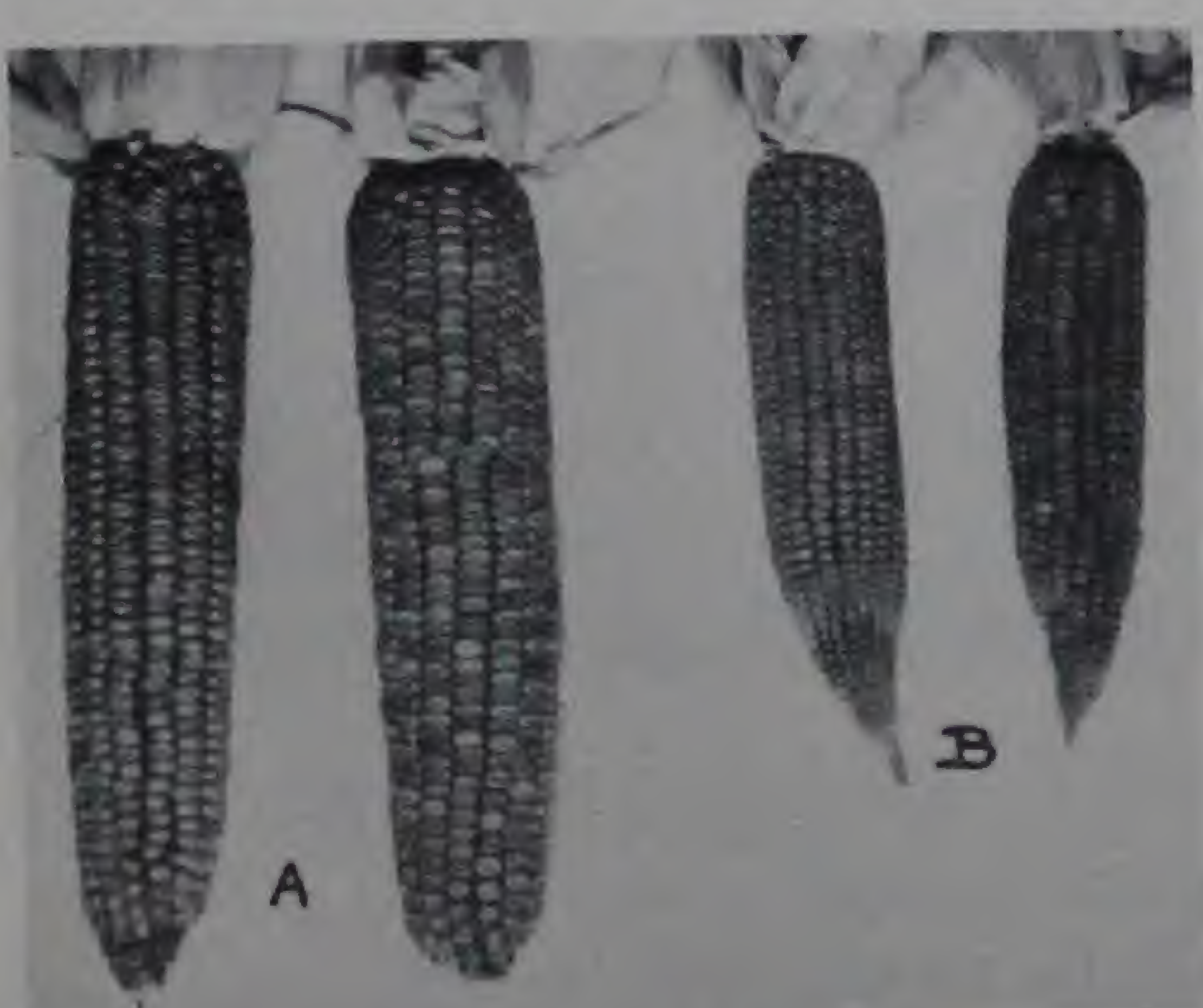


Figure 4. A, Ears on plants receiving complete fertilizer. B. Potassium-starved ears from plants receiving nitrogen and phosphorus only, are of low feed quality.

Potassium deficiencies are often expressed in a manner quite similar to certain disease symptoms, such as leaf blights (24). Since the level of soluble potassium in the plant sap is easily determined, tissue tests for potassium (17, 25, 29) are quite useful and reliable in distinguishing disease from nutritional disorders.

MAGNESIUM (Mg) DEFICIENCY

Magnesium is a component part, and the only metallic constituent, of the chlorophyll molecule. It is also an activator and component of many plant enzymes. It is fairly mobile in the plant, so that the first deficiency symptoms usually appear on the older, mature leaves. Most plants will contain from 0.1 to 0.5 percent total magnesium.

Magnesium deficiency in corn has been reported in various parts of the southern states and in Massachusetts (20). It is most often found in acidic sandy soils, particularly in the Atlantic coastal area. Magnesium

deficiency in small grains is less common than in corn, but Chucka and Lovejoy (11) did increase yields of wheat, oats, barley, and rye with magnesium fertilizers. To date, no reports have been made of magnesium deficiency in sorghum.

Symptoms: In corn seedlings the first symptoms appear on the lower leaves as a general yellowing in color due to loss of chlorophyll. Eventually the areas between the veins of the leaves become light yellow to almost white while the veins themselves remain fairly green, giving rise to a definite striping (see plate 7). As the deficiency progresses the leaves take on a reddish-purple color along their edges and tips, starting with the lower leaves and working upward. Under severe deficiences the tips and edges of the lower leaves may die and the entire plant may show the characteristic inter-veinal striping. While some stunting of the plants occurs this symptom seldom is as severe as in phosphorus or potassium deficiency.

Magnesium deficiency symptoms in wheat grown in nutrient solution cultures is shown in plate 12C. In the field, magnesium deficiency causes a dwarfing and yellowing of small grain plants. However, this symptom is not distinctive and is difficult to differentiate from symptoms of diseases and other deficiencies without the aid of plant tissue tests.

SULFUR (S) DEFICIENCY

Corn, sorghums, and small grains have relatively low requirements for sulfur compared to alfalfa, clover, cabbage, and related crops.

Sulfur deficiency in field grown corn was first reported by Fox and Hoover (14) in Nebraska in 1959. They found that sulfur applied in fertilizer increased early growth, hastened maturity, and improved yields. They reported several cases of early growth response to sulfur but no yield response. Figure 5 shows an example of this.

Sulfur deficiency in wheat and barley was reported in 1951 by Reisenauer and Leggett in Washington (36). They found responses to sulfur greatest at high levels of nitrogen fertilization. Sulfur deficiency in small grains also has been reported in many parts of the world including Australia, Brazil, and Canada (21).

Symptoms: Sulfur deficiency symptoms in corn or sorghum are stunted growth, delayed maturity, and a general yellowing of the foliage. However, in some cases an interveinal pattern appears, the veins remaining green (plate 8A). Fox and Hoover (14) noted that when this pattern is pronounced, it could be mistaken for deficiencies of iron or zinc. How-

ever, zinc deficiency occurs mainly on alkaline soils while sulfur deficiency usually is found in acid soils.

Sulfur deficiency in small grains causes stunted growth, delayed maturity, and general yellowing of the foliage. This yellowing of the leaves also is characteristic of nitrogen deficiency. However, in the case of nitrogen, the yellowing usually begins with the older leaves and proceeds

Courtesy of Nebraska Agricultural Experiment Station

Figure 5. Sulfur response in corn—Note the superior size and color of the corn on the left which received sulfur application. This effect may or may not carry through to maturity. In this case there was only a two bushel increase from sulfur application.

upward. In sulfur deficiency, the yellowing is usually more marked in the younger leaves. The rapid nitrate tests (6, 41) can be used in the field to differentiate between nitrogen and sulfur deficiency in corn, sorghums, and small grains. If the nitrate content is adequate, the yellowing may be attributed to sulfur deficiency.

CALCIUM (Ca) DEFICIENCY

Calcium is essential for the growth of all plants. It is a constituent part of cell walls, and affects the permeability of protoplasmic membranes

that surround each living cell. It controls uptake of water by cell colloids. Leaves usually contain the largest amounts of calcium found in plants, 0.2 to 1.0 per cent, although many roots are high in this element.

Symptoms: Calcium deficiency in field crops seldom is encountered. While calcium deficiency in corn has been reported under field conditions (30) its occurrence is extremely rare. Calcium deficiencies in small grains under field conditions have not been reported.

In corn, calcium deficiency is indicated by inability of the leaves to unfold or emerge. The tips of leaves stick together, giving a ladder-like appearance to plants (plate 8B). Affected plants usually have a slight yellow-green tint and are severely stunted. In extreme cases the growing tips of the plants die.

A similar ladder-like symptom often appears in corn when a young plant has been covered with soil during improper cultivation. Under such conditions the leaves of the plant are kept from unfolding by the weight of the soil covering the leaf tips. Examination of such plants shows an absence of the sticky gelatinous substance that causes the tips of calcium deficient leaves to stick together.

ZINC (*Zn*) DEFICIENCY

Zinc deficiency in field grown corn was first found and corrected by Barnett and Warner (1) in 1935. Viets (43) made an intensive study of zinc deficiency problems in corn and other crops in Washington. In more recent years zinc deficiency has been found in many areas, particularly in the Southeast and the West. In a micronutrient survey, Berger (2) reported zinc deficiency in corn in 20 states. Although zinc deficiency is not prevalent in the central part of the Corn Belt, it was reported recently in Indiana.

Since corn is most sensitive to lack of zinc and shows an easily recognizable symptom, it is an excellent crop for identifying zinc deficient soils. In the West, zinc deficiency is most prevalent in areas where the top soil has been removed from land by leveling for irrigation purposes (22). In normal ungraded soils where plants have been growing for some time, available zinc in the surface soil often is double that of the subsoil. Deep cuts in a soil that is moderately low in available zinc may expose zinc deficient subsoils. Zinc deficiency is found on a wide range of soil textures and pH conditions, but it is most often found in sandy and/or calcareous soils.

Zinc deficiency is more severe during cool, wet weather. In the

Coachella Valley, California, winter grown sweet corn may show severe zinc deficiency on soils where no zinc deficiency occurs in the same crop grown in summer (42). Thus, a cool wet spring is a good time to locate and diagnose potentially zinc deficient areas. Heavy or excessive use of phosphate fertilizer may accentuate zinc deficiency on some soils (10, 39). However, this relationship does not appear to be consistent in all soils (5, 38). Liming acid soils may also bring out zinc deficiency, especially in sandy areas (39).

Symptoms: Corn shows the most definite and easily recognizable zinc deficiency symptom of any annual field or vegetable crop. In severely deficient areas, this symptom occurs within two weeks after seedling emergence. It is characterized by a broad band of bleached tissue on each side of the midrib, beginning at the base of the leaf as is shown in plate 9. This symptom occurs mainly in the lower half of the leaf and may be seen when the young leaf is coming out of the whorl. The midrib and the leaf margin remain green. Zinc deficient plants also are stunted and have short internodes. Lingle (27) reported that reddish or brownish areas often occurred on the older leaves, and many tassels were devoid of anthers.

Early workers (1) ascribed the name "whitebud" to zinc deficiency symptoms of corn. Viets (43) and others, including the authors, believe that "whitebud" is an inappropriate term for zinc deficiency symptoms of corn since the buds or tips of new leaves usually remain green and the bleached or white areas occur in the lower portions.

Mild zinc deficiency may show an interveinal striping somewhat similar to that of manganese or iron deficiency. However, if manganese or iron is lacking, the interveinal striping runs the full length of the leaf while in zinc deficiency it occurs mainly on the lower half of the leaf. Mild zinc deficiency symptoms commonly show up only in the seedling stage and disappear by midseason. However, even in the case of mild zinc deficiency silk emergence may be delayed and irregular. In sweet corn production this has caused a reduction in yields of marketable ears (42) even though total yields were not reduced.

Zinc deficiency on sorghum is similar to that of corn, except that less interveinal striping is noticed and a more definite white band formation is observed in the lower parts of the leaves.

In the case of small grains, the symptoms are not so definite and can be more easily confused with other nutrient deficiency symptoms. Zinc deficiency has been observed in small grains in numerous areas, including Australia and California.

Plant symptoms which are believed to be caused by zinc deficiency may be verified by plant or soil analyses (7, 8, 15, 32), or a foliage spray with zinc compounds.

IRON (Fe) DEFICIENCY

Iron chlorosis is most common in calcareous soils (those containing free calcium carbonate). In the annual crop group, sorghum is one of the most sensitive to iron deficiency. In areas where forage or grain sor-

Courtesy of University of California, Division of Agricultural Sciences

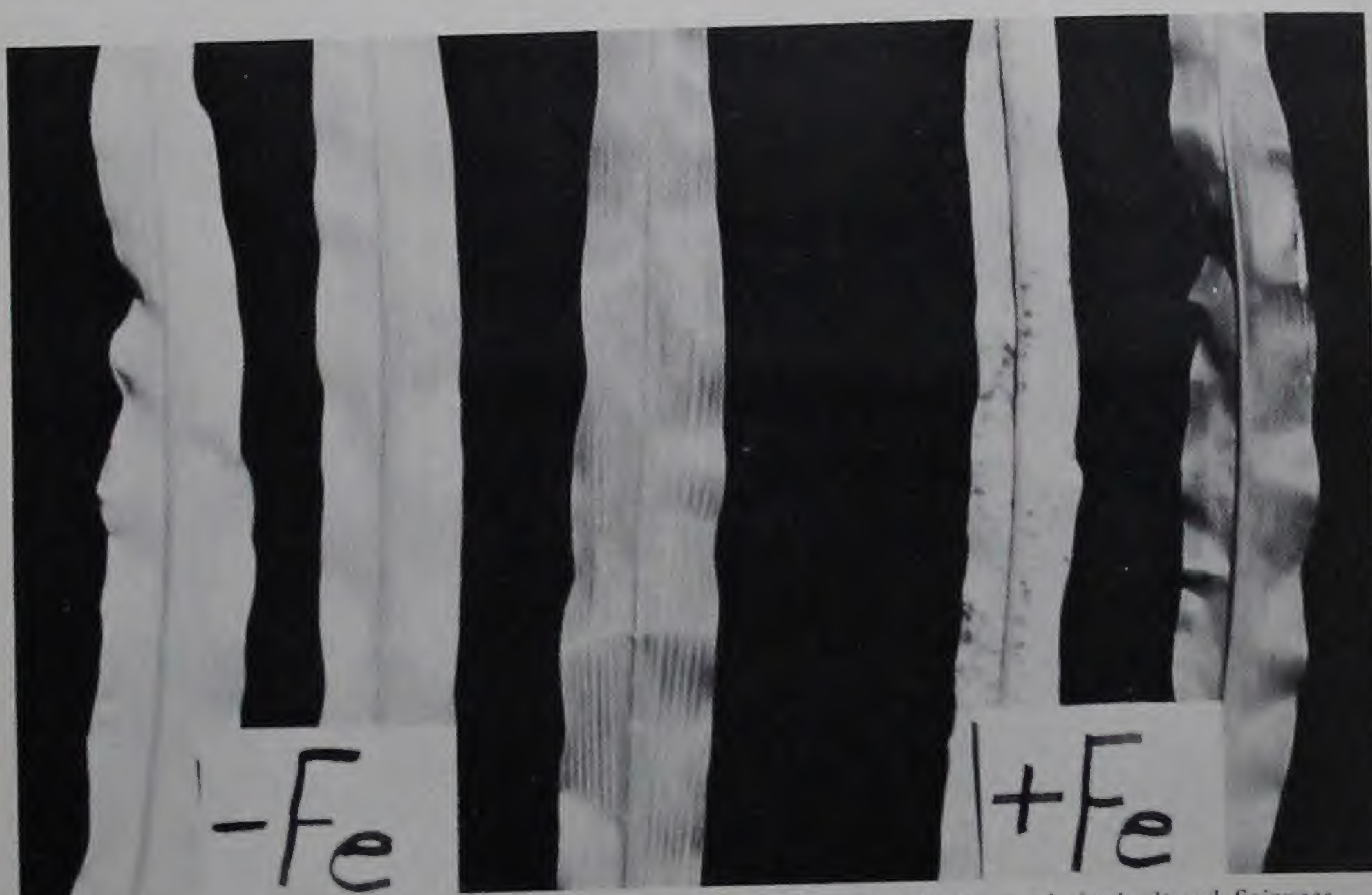
Figure 6. Plants on the left received two foliar applications of 3 per cent ferrous sulfate solution at 50 gallons per acre and produced 4,000 pounds of grain per acre. Chlorotic plants on the right received no spray and yielded only 250 pounds of grain per acre.

ghums are harvested and allowed to re-grow for a second crop, the regrowth shows iron chlorosis much more severely than the first growth (23).

Iron chlorosis on sorghum and related crops can be corrected either by foliage sprays or by soil applications of iron compounds. However, soil applications have been economically impractical because of the large amounts required. Workers in Texas (13), Kansas (45), and California (23) have shown that foliage sprays with ferrous sulfate solution are the most effective and economical means of correcting iron

chlorosis (see plate 10B and figure 6). The concentrations used by these workers ranged from 2.5 to 4 percent ferrous sulfate solution. The number of sprays required varied from one to three, dependent upon the severity of the chlorosis. Ferrous sulfate used in these trials was a commercial grade of copperas ($FeSO_4 \cdot 7\ H_2O$) containing 20 percent iron.

Iron deficiency in non-calcareous soils usually is caused by excessively high levels of phosphorus, copper, manganese, and/or zinc (9).



Courtesy of University of California, Division of Agricultural Sciences

Figure 7. The three leaves on the left show varying degrees of iron chlorosis. The leaf on the right side came from a plot where the iron chlorosis had been corrected by a foliage spray. The second leaf from the right is from an adjacent plot that received only slight coverage which shows as green spots on the leaf. This demonstrates the need for good coverage of the ferrous sulfate spray.

Rice grown on high pH, non-saline, high sodium soil under flooded conditions responded markedly to applications of ferric sulfate (19). However, under non-flooded conditions rice grows normally without iron additions.

Symptoms: Sorghum shows an easily recognizable symptom and is a good indicator crop to detect iron deficiency. Iron chlorosis in sorghum and related crops can be identified by the interveinal chlorosis or striping which extends the full length of the leaves (see plate 10A and figure 7). The chlorosis starts and is most severe on the upper leaves. In cases of severe iron deficiency, plants become white and eventually die.

Iron chlorosis on corn is similar to that of sorghum, but corn is less sensitive to iron deficiency. Iron chlorosis symptoms on small grains are similar to those of corn and sorghum, but in small grains they are more easily confused with diseases and other abnormalities. Certain grass weeds such as water grass and Johnson grass are sensitive to iron deficiency and may serve as indicator plants.

Iron deficiency cannot be diagnosed readily by any known method of soil or leaf analysis. Foliar spray is the best means to verify the symptom. Iron deficiency in soils usually can be diagnosed in pot culture using sorghum as the indicator crop.

MANGANESE (Mn) DEFICIENCY

Manganese deficiency in corn, sorghum, and small grains is not very common, although it has been reported in several states (2) and in almost every country of the world. The small grains, especially oats, are much more sensitive to low manganese levels in soils than are corn or sorghum. Where manganese deficiencies occur, the soils usually are either calcareous, extremely sandy, or high in organic matter.

Manganese has been associated with many functions in the plant. Its role in chlorophyll development was first noted by Bertrand (4) in 1897. Since then many functions, as indicated by Mulder and Gerretsen (31), have been ascribed to manganese, including catalytic, regulatory, and enzymatic. It is known to be required in the nitrogen metabolism of plants, photosynthesis, and carbohydrate breakdown, and it probably has other functions as yet undetermined. Its absorption by plants appears to be temperature dependent.

Symptoms: Among the small grains, oats are the most sensitive to manganese deficiency and, therefore, the most likely crop to show the deficiency in any area. Oats also have the severest and most easily recognized symptoms among the small grains. Mulder and Gerretsen (31) have described the manganese deficiency symptoms in oats as follows: "Marginal gray-brown colored necrotic spots and streaks appear first on the third highest leaves, particularly on the basal half. The streaks tend to elongate and coalesce. At the distal ends of the affected basal part the necrotic spots may soon extend across the blades so that the upper half or two-thirds of the leaf falls over with a sharp kink as the collapsed portion. The distal ends of the leaves remain green for a considerable time. On older leaves the collapse may be confined to the lower quarter, and oval spots of necrotic tissue may appear irregularly on the leaf

blade, though less frequently toward the tip end." "Gray-speck disease," and "halo blight" are terms often used to describe the gray-brown necrotic spots on the leaves of the small grains.

In corn and sorghum, manganese deficiency symptoms are quite vague and seldom observed under field conditions. Usually about the only symptoms that appear are a slight stunting of growth and a slight color loss between the veins of the upper younger leaves, but these symptoms are not characteristic solely of manganese deficiency. Because of its variety of functions in plants, mild manganese deficiency symptoms seldom are very striking or pronounced and seldom can be diagnosed visually. Field symptoms of manganese deficiency in crops always should be supported with tissue tests.

COPPER (Cu) DEFICIENCY

Copper plays a role in the action of many oxidizing enzymes which function in respiration. It also may be associated with chlorophyll formation.

Copper deficiency in field crops occurs mainly on organic soils including peat and muck (2). Small grains, especially oats, are more sensitive than corn to copper deficiency.

Symptoms: In corn, copper deficiency symptoms appear first on the youngest leaves of the plant. Generally they appear more frequently on younger plants than on older or more mature growth. The first symptoms are a yellowing of the upper, or youngest, leaves and a slight stunting in growth. Under severe deficiency the plant is severely stunted, the younger leaves become a very pale yellow, and some "die-back" of the older leaves occurs (plate 11). Finally, areas of dead tissue appear along the tips and edges of the leaves, in a pattern somewhat similar to potassium deficiency symptoms. Plants showing such severe copper deficiency symptoms seldom mature and usually die during the early or middle part of the season.

In small grains, copper deficiency is characterized by a loss of color in the younger leaves, followed by a breaking of the leaves, and eventual dying of the leaf tips. In more extreme cases the leaves become shriveled, twisted, and broken, and the plant dies.

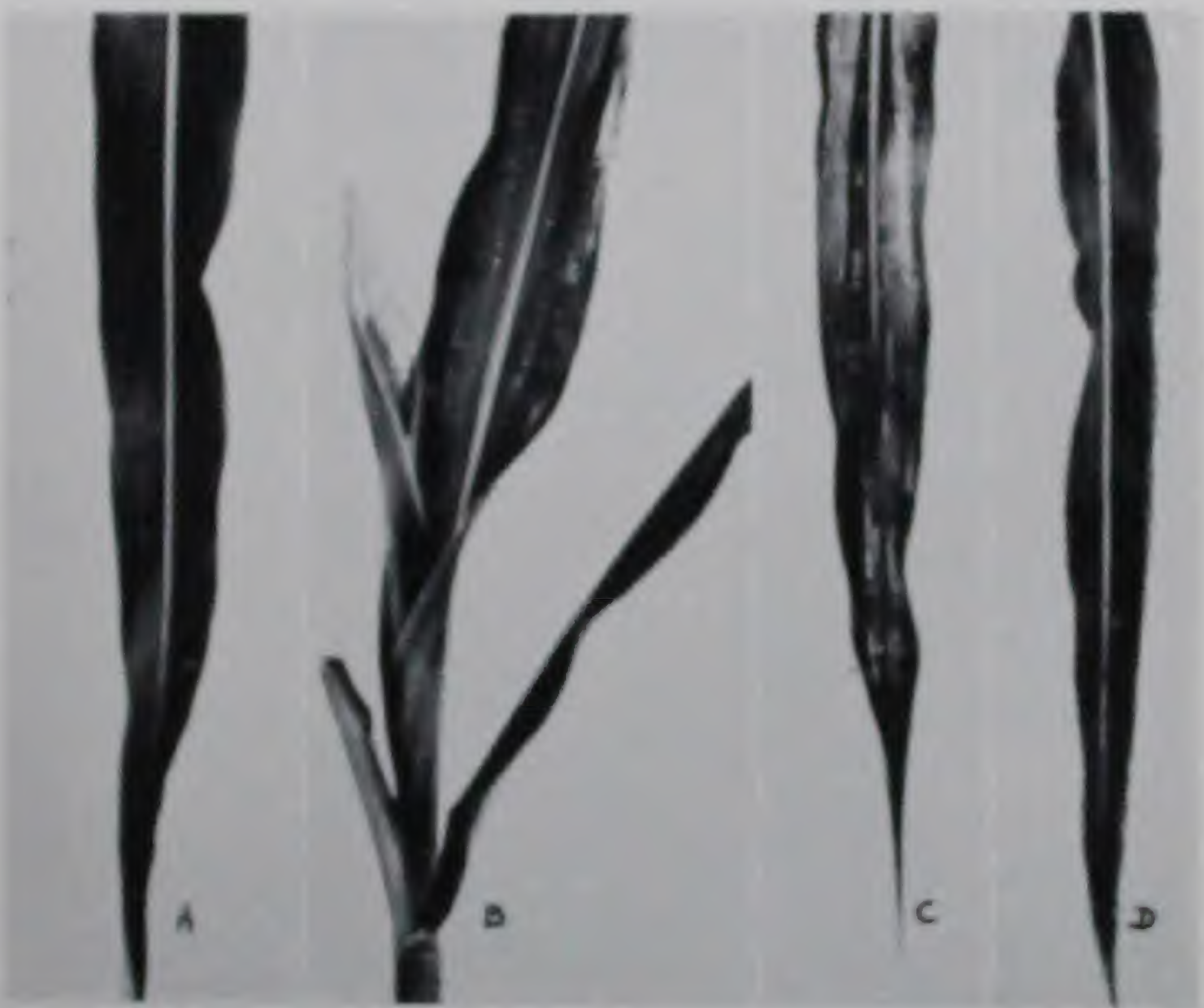
BORON (B) DEFICIENCY

Boron deficiency is very widespread in the United States, particularly on legumes and sugar beets and certain vegetable crops (2). Corn and

other cereals, however, appear to have a low demand for boron and reports of boron deficiencies in these crops are quite infrequent. Nusbaum (33) in 1948 was the first to report boron deficiency symptoms of corn growing under field conditions.

The importance of boron in promoting flower and seed production of corn was shown in nutrient solution culture studies (28). Berger (3) concluded that a continuous supply of boron in the nutrient solution is essential for production of ears and kernels, and that lack of it can cause barren plants. Berger further reasoned that some of the barren plants in

Figure 8. Corn leaves. A, normal leaf. B, Boron-starved plant; youngest leaves and tip of shoot dying. C, Older leaves develop yellowish-white stripes. D, Boron toxicity causes an edge scorch, very similar in appearance to a symptom of potassium starvation.



high production corn fields might be due to boron deficiency. In an extensive study involving 54 fields, he found that boron application increased corn yields and reduced the number of barren plants in 6 of the test areas.

Berger found a poor correlation between soil boron content and plant response. He pointed out that this is to be expected since boron availability is greatly affected by climatic influences such as leaching and drought. From preliminary plant analysis studies, he suggests that the critical minimum level in upper corn leaves is 11 to 13 ppm (parts per million) of boron (3).

Symptoms: The leaf symptoms of boron deficiency are shown in figure 8. Boron deficiency is seen first on the youngest leaves as white,

irregularly shaped spots scattered between the veins. With severe deficiency these spots may coalesce forming white stripes 1 to 2 inches long. These white stripes appear to be waxy and raised from the leaf tissue. There is also a shortening of internodes and often the young leaves fail to unfurl (3).

In nutrient solution culture studies, Berger (3), found failure of flowering and ear development at levels which were high enough to prevent leaf deficiency symptoms. Thus, flower and seed development

Figure 9. Ear healthy boron-tested corn plant, and three ears from boron-deficient plants (left to right). Note one-sided shriveling of kernels on the three ears from the no-boron plot.

failure should be considered as a boron deficiency symptom. An example of the poor seed development symptom is shown in figure 9 (33).

To date there have been no reports of symptoms attributed to boron deficiencies in fields of sorghum or small grain in this country.

In desert and semi-arid regions, certain soils and irrigation waters may contain toxic concentrations of boron (44). Figure 8D shows a marginal scorch caused by boron toxicity. Boron toxicity on barley is characterized by elongated, dark-brown blotches. This symptom occurs first at tips of the older leaves.

MOLYBDENUM (Mo) DEFICIENCY

Cereals and grasses appear to be rather insensitive to molybdenum deficiency and thus are not good indicator crops to identify deficiency of this element in the field. No reports have been noted of molybdenum deficiency in field grown corn, sorghum, or small grains in the United States. Molybdenum deficiency has been reported in field grown corn, wheat, oats, and rye in New Zealand. In solution culture, Peterson and Purvis (34) found that the molybdenum content of corn seed was sufficient for normal growth. They found that it was necessary to develop corn seed low in molybdenum before deficiency symptoms could be produced. This also was true of other large seeded crops, such as cotton and soybeans.

Symptoms: Peterson and Purvis (34) described molybdenum deficiency symptoms of corn as follows: "The older leaves died at the tips, then along the margins, developed necrosis between the veins, and died. The younger leaves first wilted and then died along the margins, and in some cases became twisted." Hewitt (16) gives detailed descriptions of molybdenum deficiency in oats, barley, wheat, and rye as well as other crops.

SUMMARY

The plant diagnostician should use all of the "tools" available to him. This includes soil, plant and water analyses, nutrient deficiency symptoms, pot culture assays, and field experiments. In using visual symptoms as a diagnostic aid, he should realize that diseases, toxicities, insects, nematodes, or mechanical injuries may produce symptoms similar to those produced by certain nutrient element deficiencies. A visual symptom found on a single plant is usually caused by a disease, an injury, or a genetic variation. Nutrient deficiency symptoms usually occur on several plants over a broad area following a soil or management pattern. Visual symptoms of a given nutrient deficiency are more distinct on some plants than others. When you suspect a certain nutrient deficiency look for "indicator" plants.

Nutrient deficiency symptoms provide the fastest means of diagnosing plant nutrient problems, but also require the most experience.

The following key gives a brief summary of "hunger signs" in corn.

KEY TO NUTRIENT DEFICIENCY SYMPTOMS OF CORN

I. Stunted Plant .... common to all deficiencies
II. Loss of green color .... common to all deficiencies

	Element Deficient
A. Color changes in lower leaves:	
1. Yellow discoloration from tip backward in form of a V	Nitrogen
2. Brown discoloration and scorching along outer margin from tip to base	Potassium
3. Yellow discoloration between veins, finally edges become reddish-purple	Magnesium
4. Purpling and browning from tip backward, in waves	Phosphorus
5. Uniform yellowing of upper and lower leaves	Sulfur
B. Color changes in upper leaves:	
1. Emerging leaves show yellow to white bleached bands in lower part of leaf	Zinc
2. Young leaves show interveinal chlorosis along entire length of leaf	Iron
3. Young leaves uniformly pale yellow, older leaves dying at the tips	Copper
4. White, irregular spots between veins	Boron
5. Young leaves show pale green to yellow discoloration between veins	Manganese
6. Young leaves wilt and die along the margins	Molybdenum

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Courtesy of North Carolina Agri. Exp. Sta., U. S. Dept. of Agri. and American Potash Institute

Plate 1. Corn plant at left A shows severe nitrogen deficiency. Note yellowing begins at tip of lower leaves and proceeds up the midrib, giving a V-shaped pattern. Plant B in center shows symptoms of extreme drought. Dry-weather injury can be distinguished from nitrogen deficiency inasmuch as drought affects the upper as well as the lower leaves. Severe potassium deficiency shows up in the plant C on the right as a marginal scorch affecting the lower leaves first.

Courtesy of North Carolina Agri. Exp. Sta. and U. S. Dept. of Agri.

Plate 2. Nitrogen made the difference! Nitrogen at the rate of 180 pounds per acre was applied to the corn on the left. The corn on the right received no added nitrogen. The yields were 110.3 and 24.4 bushels per acre, respectively.

Plate 3. Phosphorus hunger causes purpling of the leaves of many strains of corn.

Plate 4. A, Normal corn leaf. B, Nitrogen-starved leaf. The yellowing begins at tip end and progresses along the midrib. C, Potassium-starved leaf. Note characteristic brown edge scorch.

Plate 5. Potassium starvation results in weak corn stalks with the leaves badly damaged. The marginal "firing" affects all the leaves.

Courtesy of North Carolina Agri. Exp. Sta. and U. S. Dept. of Agri.

Plate 6. Potassium-starved young corn plant. The lower leaves show the typical marginal scorch. At this stage of growth in the field it is possible to apply remedial side dressings of potash salts profitably.

Courtesy of Massachusetts Agricultural Experiment Station

Plate 7. Magnesium-starved corn. The regular yellowish-white stripes on the leaves indicate the deficiency.

Courtesy Illinois Agricultural Experiment Station

Plate 8. A (above), Sulfur deficiency in corn. Note yellowing of the leaves particularly between the veins. B (left), Calcium deficiency in corn. The tip ends of the leaves are glued together.

Courtesy of University of California, Division of Agricultural Sciences

Plate 9. Zinc deficiency in corn. Note the broad bands of bleached tissue in the lower half of the leaf. The midrib and leaf margins remain green. (See text for more complete description.)

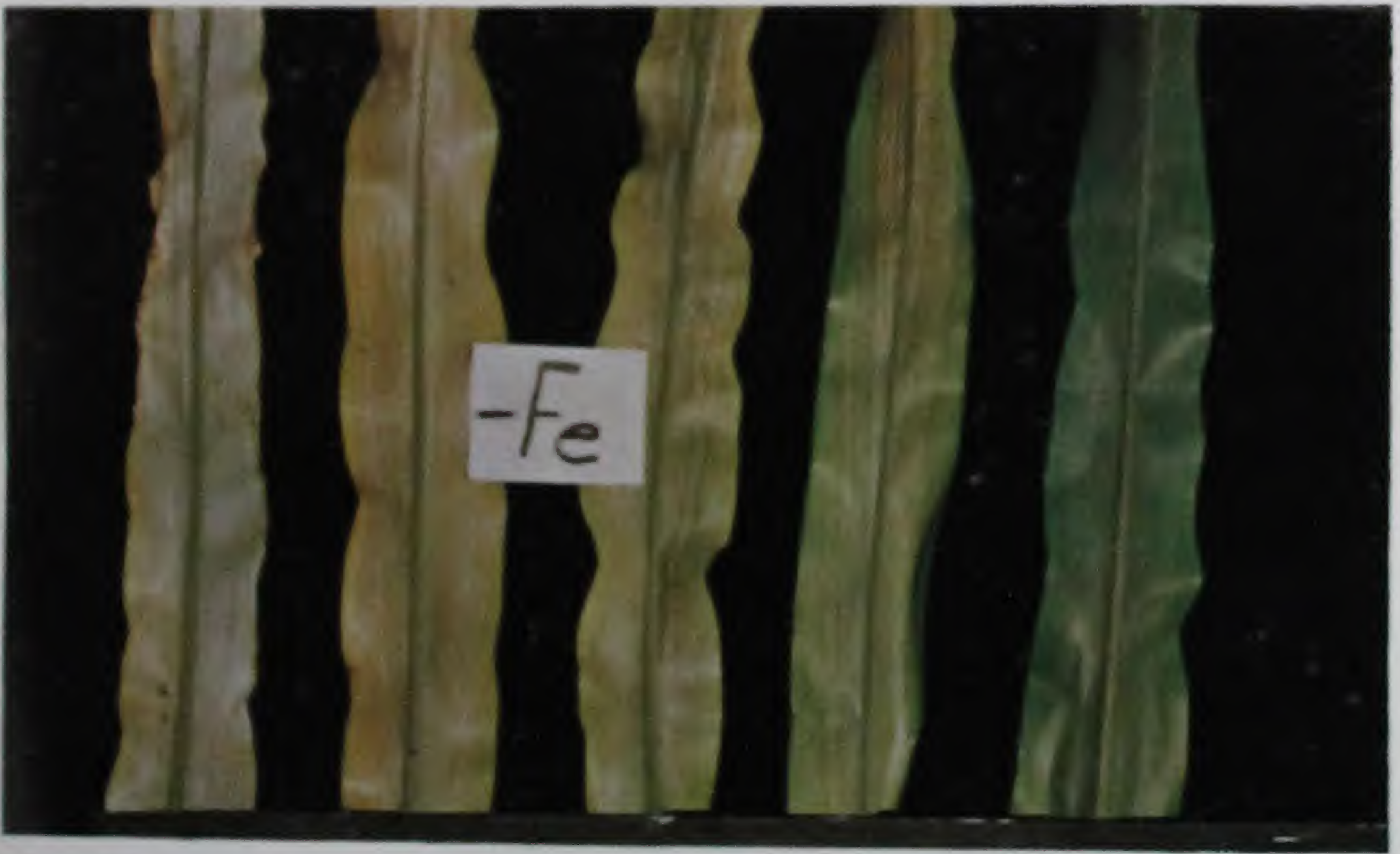

Plate 10A. Iron deficiency in sorghum, grading from severe deficiency on the left to a normal leaf on the right. Note that the interveinal chlorosis extends the full length of the leaf. The deficiency is most severe on the youngest leaves.

Courtesy of University of California, Division of Agricultural Sciences.

Plate 10B. Eighteen days before this picture was taken the plants on the left had been sprayed with 3 per cent ferrous sulfate solution at the rate of 50 gallons per acre. These plants turned green within 6 days after the foliar application.

Plate 11. Copper deficiency in corn. Upper leaves show a pale yellow color; the leaf tips curl; and the older leaves dieback.

C and D, courtesy of Purdue University Agricultural Experiment Station

Plate 12. A, Nitrogen-starved oat leaves. Nitrogen hunger causes the leaves to yellow and die. B, Phosphorus-starved oat leaves. The leaves die gradually from the tip ends with no particularly distinctive coloration. Note close similarity to the nitrogen-starved oat leaves. Chemical tests of the tissues are needed to confirm this symptom in the field. C, Magnesium-deficient wheat leaves. A slight mottling of the leaves was obtained in controlled nutrient cultures. D, Purplish-brown spots on barley leaves indicate potassium deficiency. These spots precede the usual marginal and tip-end "firing" of potassium-starved leaves. Cause of spots unknown.

Plate 13. A, Healthy green leaf of wheat showing balanced fertility. B, Yellowish-green leaf with tip end turning yellow indicates nitrogen starvation. C, Dark-green leaf with the tip end dying indicates possible deficiency of available phosphorus. D, Leaves with the tip ends becoming yellow and scorched along the edges indicates a deficiency of potassium. These symptoms are diagnosed with difficulty under field conditions unless chemical tests for nitrates, inorganic phosphates, and potassium are made on the tissues.

Courtesy of American Potash Institute

Plate 14. Demonstration of tissue tests used for the confirmation of nitrogen and potash deficiency symptoms in hybrid corn plants.

A. Leaf and ear from well-nourished plant. Note healthy leaf and well-matured ear. Tissue tests show as follows:
(1) Medium nitrate—red color—with Bray's nitrate test powder. See selected reference (6) for description.
(2) Medium potash (3) Medium phosphate
Compare these healthy tissue tests with B and C.

B. Nitrogen-deficient plant. Note yellowish green leaf and deadened tissue along midrib. Also glossy kernels on underdeveloped ear. These kernels are low in protein, but high in fats.
(4) Negative nitrate—no color (5) Very high phosphate.
(6) Very high potash. Nitrogen-starved plants frequently accumulate luxury amounts of phosphate and/or potassium as shown in these tests.

C. Potassium-deficient plant. Note deadened marginal leaf tissues and tapered, unfilled ear with starchy kernels.
(7) Very high nitrate—deep red color. (8) Very high phosphate.
(9) Low potash. Potassium-deficient plants will accumulate luxury amounts of nitrates and/or phosphates, but cannot function properly in producing mature ears.

These tissue tests show that when one plant nutrient becomes deficient, other nutrients may accumulate in excessive amounts and further complicate the diagnosis of the deficient plant. Luxury quantities of nitrates (7), phosphates (5, 8), and/or potash (6) frequently indicate a deficiency of some other essential nutrient for healthy growth and development of the plant. Use all possible tests for nutrient elements correctly for diagnoses of deficiency symptoms! For example, the very high phosphate tests (5, 8) may be misleading when nitrates and/or potassium are deficient in the plants tested. Medium tests for nitrates (1), phosphates (3) and potash (2) indicate adequate amounts in the plants at the time of testing. They are particularly important when the ears are maturing, in order to ascertain whether all of the plant nutrients were adequately supplied in the fertilizers applied to the crop.

Chapter III

Nutrient Deficiencies in Cotton

By Leroy Donald *

COTTON constitutes no exception to the changing pattern of crops grown in America, an adjustment which accelerated about 1950. Further geographical shifts in the distribution of acreage and highly significant technological advances in the production of our major fiber crop have occurred since the last revision of the census in 1959. Each of these factors either has created new or has intensified old nutritional problems.

The increase in cotton acreage which has occurred since mid-century on all cotton-producing continents, with the lone exception of North America, implies that the crop is now being grown under a wider range of climatic conditions and soil types than ever before. Nutritional problems with their accompanying deficiency symptoms, which both climate and soil may influence, quite logically vary by countries and areas of production.

The trend in the United States, under the government's acreage reduction programs, has been toward a rapid and substantial retirement from cotton of much of the steeper or submarginal and less productive land in the South to sod-forming crops or timber. Simultaneously, the westward shift in acreage within the United States has continued with the result that cotton is being produced to a greater extent in southwestern and western states on the more alkaline soils and under the semi-arid climate which prevail in that part of the Nation. Nutritional problems, with their accompanying deficiency symptoms appearing in the crop grown under those conditions, may quite logically be expected to vary somewhat from those previously encountered in the crop grown on the more acid soils and under the humid climate which prevail in the old cotton-producing areas of the South.

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* Leroy Donald is Chief Agronomist for the Agricultural Division of Monsanto Company. This chapter in previous editions was prepared by Dr. H. P. Cooper, formerly Dean of the School of Agriculture, Clemson Agricultural College, Clemson, South Carolina, and the current author.

This shift in acreage within the United States, generally speaking, has been toward the more level lands which usually have a higher potential productive capacity. On such lands, growers often are able to produce higher yields of cotton more efficiently on a larger scale with machinery. These geographical shifts have within themselves altered nutritional problems relating to cotton, and thereby influenced the occurrence and extent of deficiency symptoms in the crop.

Advances made in production technology since mid-century have been directed toward decreasing the cost of growing cotton, higher per acre yields keynoting the effort. It is generally conceded that technological progress, more than better land adaptation, has been responsible for the outstanding cotton production record achieved by American farmers who have increased the average yield from approximately one-half bale to almost a bale per acre since mid-century. As one means of lowering production costs, many farmers have completely mechanized essential operations, the logical aftermath of which has been rapid consolidation of farms, with larger acreages of cotton being grown by major operators. The generally greater efficiency of the surviving cotton producers has quite logically resulted in a more rapid depletion of soil elements, nutritional problems, related primarily to major plant nutrients, arising sooner than otherwise would have been the case.

To protect their greater investment in land, equipment, and labor, a majority of the growers have greatly increased their rates of application of the major plant nutrients as fertilizers for the production of cotton. As a further economic measure, many farmers are purchasing and applying the more concentrated fertilizers with the result that substantial savings are being realized in costs of major plant nutrients generally required by the cotton crop. The increases in rates of application of the major nutrients, as well as prolonged use of concentrated fertilizers, logically may be expected to create new problems in nutrition related chiefly to the secondary and micronutrients. The greater amount of filler or carrier materials present in the previously-applied, low analysis fertilizers supplied minute to rather substantial quantities of secondary or micro-nutrients, which either are greatly reduced or completely eliminated in the highly-concentrated fertilizers. When and if needed, however, the secondary and micronutrient requirements of cotton usually can be acquired more economically as supplements which may be added to the concentrated fertilizers, applied on the land as such, or introduced into the plants through foliar applications (leaf sprays) in certain cases.

Irrigation, a practice which has been greatly expanded in the newer and semi-arid areas of cotton production within the United States, has more rapidly intensified nutritional problems. The resulting higher yields than would have been realized under dry-land farming conditions obviously have exacted a heavier toll of nutrients from the soil. Increased use of fertilizers in those areas has been greatly stimulated as a result of the greater efficiency with which plant nutrients are utilized by cotton grown under irrigation. Land-leveling, in turn, is being more widely practiced as an adjunct to both irrigation and mechanization. As might be expected, cotton grown on limited areas of subsoil left exposed by leveling operations, or even on inter-mixtures of topsoil and subsoil which frequently result, has exhibited certain rather uncommon deficiency symptoms in some localities.

As previously stated, and for reasons implied, production of cotton is rapidly becoming stabilized on the more level and fertile soils. Realizing that greater economy in production is possible when the crop is grown on such soils, many farmers are disinclined to rotate the crop to their steeper, less productive, and often more risky lands. An increasingly greater number of farmers are resorting to continuous production of cotton, or monoculture, a practice that is being aided and abetted by low-cost fertilizers as well as by highly effective and favorably priced chemicals now available for the control of weeds, insects, and diseases. Under the system of continuous cotton production, both quantity and management of crop residues become of paramount importance. The possibility of creating new or intensifying old nutritional problems obviously becomes increasingly greater under a monocultural system of farming.

To round out the approach to lower cost of production, research workers are continuing to breed more productive cotton varieties in their efforts to increase the yield potential, as well as to better adapt the crop to mechanization. Greater efficiency bred into a crop variety or strain generally implies higher requirements for plant nutrients. The end result can be and often is an accelerated appearance of deficiency symptoms, unless the increased requirements of the improved variety are satisfied.

The foregoing background has been supplied to provide the reader a better understanding of those factors which are currently influencing the nutrition of cotton. Furthermore, the facts as related should constitute a plausible explanation of the more widespread appearance of the

common deficiency symptoms, as well as the greater incidence of heretofore unusual "hunger signs" in the cotton crop.

The discussion of the chemical composition of the cotton plant to follow, as well as the deficiency symptoms which will be subsequently described, relate generally to American upland species which presently comprise better than 99 percent of the cotton acreage in the United States. American-Egyptian species constitute the remainder of the domestic acreage. Although certain rather marked differences appear between the two types, their general structure, habits of growth, and pattern of nutrient response are quite comparable. For more detailed information, the reader is referred to the works of Eaton (18), Reynolds (46), Tharp (49), and Wadleigh (51), who, among others, have made notable contributions to our knowledge of the structure, or morphology, and life cycle of the cotton plant.

Not all of the selected references, each of which merits careful study, are cited in the body of the text. Only those references appear in the manuscript which deal with specific aspects of cotton nutrition, or from which certain statements have been lifted that appear in the discussion of the various nutrient deficiency symptoms.

CHEMICAL COMPOSITION OF THE COTTON PLANT

In considering the nutrient-deficiency symptoms of cotton, it is highly desirable to know something about the chemical composition of the crop. That some plants selectively accumulate certain nutrients is generally recognized. The data on the average chemical composition of 28 samples of cotton plants and 8 samples of cotton seed, representing a wide variety of the soil conditions found in South Carolina, are included in Table 1.

The content of the different elements, as determined through research conducted in South Carolina, indicates that cotton is a calcium-accumulating plant. Calcium-accumulating plants apparently possess the capacity to synthesize organic acid complexes capable of forming low-solubility calcium compounds, which characteristic probably results in a fairly constant calcium content within the cotton plant. Only a relatively small quantity of silicon was absorbed by the cotton plant under the conditions of the experiment conducted in South Carolina.

Since some of the soils in the native habitat of cotton may have contained a soil horizon of calcium carbonate accumulation, it is logical to expect that the cotton plant would possess the capacity to tolerate fairly high concentrations of calcium ions. As indicated, the nitrogen,

TABLE 1.—COMPARATIVE AVERAGE CHEMICAL COMPOSITION OF 28 COTTON PLANTS AND 8 COTTON SEED SAMPLES

The elements are arranged according to relative strength of ions as expressed in standard electrode potentials or discharge potentials of acids on platinum electrodes.

Material	*Ion*	*Normal Electrode Potentials in Volts*	*Percent Dry Matter*		*Percent of K Values* (K = Potassium)	
			Plant	*Seed*	*Plant*	*Seed*
Potassium	K^+	+2.92	0.830	0.129	100.00	100.00
Sodium	Na^+	+2.71	0.450	0.012	54.22	1.06
Calcium	Ca^{++}	+2.50	1.700	0.077	204.82	6.82
Magnesium	Mg^{++}	+1.55	0.453	0.365	54.58	32.33
Aluminum	Al^{+++}	+1.30	0.040	0.006	4.82	0.53
Manganese	Mn^{++}	+1.10	0.030	0.001	3.61	0.09
Iron	Fe^{++}	+0.43	0.056	0.007	6.75	0.62
Silicon	....	....	0.093	0.011	11.20	0.97
Sulfur	HSO_4^-	−1.69*	0.280	0.565	33.73	50.04
Phosphorus	$H_2PO_4^-$	−1.70*	0.240	0.684	28.92	60.58
Chlorine	Cl^-	−1.36	0.750	0.036	90.36	3.19
Nitrogen	NO_3^-	−1.69*	1.910	4.040	230.12	357.84

* Discharge potentials on platinum electrodes.

potassium, chlorine, magnesium, and sodium contents of the cotton plant are relatively high. The rather high nutrient content of the cotton plant suggests the desirability of adding liberal quantities of a complete fertilizer to many of the soils used for the production of cotton. The relatively high content of nitrogen, phosphorus, and sulfur in cotton seed also indicates the need for a liberal available supply of these nutrients in its production.

From the viewpoint of net plant nutrient removal from the soil, however, cotton is less exacting than many major field crops. This may be attributed to the fact that the vegetative portion of the crop generally is returned to the soil. When residues are so handled, at least 75 percent of the total seasonal production of dry matter is returned to the soil. Failure to return the burs, or dried empty bolls, when cotton is harvested by stripping or snapping, obviously results in the removal of a considerably greater quantity of plant nutrients.

Perhaps the prevailing opinion that cotton is hard on the soil is largely based on the observed rapid depletion of much land devoted to cotton production in the past in the southeastern states. Possibly clean culture and the earlier use of steeper lands, which resulted in greater erosion losses, constituted the basis of this popular belief.

Approximate amounts of the various soil-derived nutrients contained in the above-ground parts of cotton plants producing at the rate of 1 bale per acre, according to the National Plant Food Institute (8), are as follows:

Plant Nutrient	In 1,500 Pounds Seed and Lint	In 2,000 Pounds Stalks, Leaves, and Burs	Total Removal
		pounds	
Primary Nutrients:			
Nitrogen (N)	40	35	75
Phosphorus (P)	8.7	4.4	13.1
Potassium (K)	12.5	29.0	41.5
Secondary Nutrients:			
Calcium (Ca)	2	28	30
Magnesium (Mg)	4	8	12
Sulphur (S)	2	0	2
Micronutrients:			
Zinc (Zn)	0.32	0	0.32
Manganese (Mn)	0.11	0	0.11
Copper (Cu)	0.06	0	0.06
Boron (B)	Trace	Trace	Trace
Iron (Fe)	"	"	"
Chlorine (Cl)	"	"	"
Molybdenum (Mo)	"	"	"

On the basis of the quantitative requirements of the respective nutrients by the cotton crop, deficiencies logically may be expected to occur in the descending order of major, secondary, and micronutrients.

DEFICIENCY SYMPTOMS IN THE COTTON PLANT

Only a very limited number of carefully controlled experiments have been conducted to date with cotton grown in nutrient cultures. Since deficiency symptoms usually described in this crop are those commonly corrected by the addition of certain fertilizer materials, most of which contain at least trace amounts of nutrients other than the one of primary concern, some questions regarding possible interaction effects quite logically may arise.

The capacity of the cotton plant to accumulate calcium, to synthesize acid-organic compounds, and to develop an extensive taproot system may partially account for the lack of widespread deficiencies of micronutrients, such as zinc, manganese, copper, boron, iron, and molybdenum. This intensifies requirements for such substances as potassium or ammonium, and enables the plant to maintain a supply of available carbonate ions necessary in the production of a high-yielding carbonaceous fiber crop.

Differentiation between symptoms resulting from a lack of available nutrients in cotton plants and those due to the action of diseases and insect pests is not always possible. Even when an abundance of the required nutrients are in the soil and are immediately available to the plants, their utilization may be affected by injuries caused by diseases and insects, with resulting deficiency symptoms. Situations of this nature may lead to much confusion in interpreting experimental results unless all the factors involved are carefully considered.

Furthermore, the appearance of deficiency symptoms in cotton does not always imply that the respective nutrients to which they are attributed are necessarily in short supply in the soil. Their solubility and availability can be materially influenced by any one of several factors, with the result that they are not absorbed and utilized in sufficient amounts. Whereas certain nutrients are only slightly soluble in the soil solution, others are highly soluble. Climatic conditions may thus adversely affect their solubility and availability to the plants. Prolonged droughts during the growing season may prevent optimum absorption and utilization of certain nutrients. Certain highly soluble nutrients, such as nitrates, on the other hand, may be readily leached from the soil during excessively wet periods over the growing season and thereby be lost to the plant. The form in which accompanying nutrients occur also may influence the rate and degree of loss of a given element.

The soil reaction also affects the solubility and subsequent availability of certain nutrients. In strongly acid soils, for instance, certain nutrients may be readily soluble and thereby available to the growing crop in adequate quantities. (See fig. 2, Chapter 1.) Application of large amounts of liming materials to correct the acidity of such soils may, in turn, decrease the solubility and degree of availability of certain nutrients with a resulting appearance of deficiency symptoms in the cotton plant.

The rate of growth of cotton is another factor which may influence the appearance of deficiency symptoms. With slow growth, soil nutrients may dissolve and become available fast enough to meet the needs of the crop and thereby prevent the appearance of deficiency symptoms. The slow rate of solubility of certain other nutrients, on the contrary, may result in insufficient amounts being absorbed and utilized by fast-growing plants with a resulting increase in the appearance of deficiency symptoms.

The foregoing points up the necessity of maintaining a proper balance of nutrients in readily available form and consistent with the most desir-

able soil reaction, if optimum yields of cotton are to be realized. It also reveals that insufficient moisture during certain critical periods of growth, even though all nutrients are present in adequate supply, can result in decreased yields. In cotton, for instance, a lack of adequate moisture during the formative stages of the lint can reduce length and otherwise lower the quality of the fiber.

In considering the descriptions of individual nutrient deficiencies which follow, readers should keep the previously discussed limitations in mind. Incident to the descriptions, the important functions of each nutrient in plant growth are briefly reviewed. Furthermore, some significant aspects of the relationship of soil characteristics, climatic conditions, and plant composition to nutritional deficiencies and the fertilizer needs of the cotton plant are related. Acknowledgement is herewith made to various authors of the U.S.D.A. 1957 Yearbook of Agriculture, "Soils" (50), from whose sectional discussions of the respective nutrients certain of the statements to follow have been drawn.

NITROGEN (N) DEFICIENCY

Since nitrogen is required by crops in greater amounts than any of the other soil-derived elements, and since it is among those most easily lost from the land, symptoms resulting from a deficiency of this nutrient in cotton quite logically are widespread. By the same token, nitrogen shortage, among all other nutrient deficiency symptoms, perhaps is the most readily and generally recognized by cotton growers.

As a key component of proteins, nitrogen usually is concentrated in the growing points of a plant where it influences both rate and extent of growth. Nitrogen also is found in abundance in the leaves of plants where, as a component of chlorophyll, it is vital to carbohydrate production. Finally, much of the nitrogen absorbed by the plant eventually finds its way into the seed where it is an essential constituent of the contained proteins. In between these implied stages of plant development, nitrogen plays many other highly important roles, all of which readily explain the essentiality of nitrogen to plant growth.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

As would be expected, the severity of nitrogen deficiency symptoms usually is greater in cotton grown on steep and coarse-textured soils in which the organic matter content is low and from which this nutrient can more readily be lost through erosion and leaching. In the

absence of applied nitrogenous fertilizers, the time and extent of deficiency symptoms often are affected by climatic conditions which retard decomposition of soil organic matter and release of nitrogen, as well as by the amount of native organic matter present in the soil.

LEAF SYMPTOMS

A pale, yellowish-green color of its leaves, which are considerably reduced in size, is perhaps the most striking symptom of nitrogen deficiency in cotton. Under extremely low levels of soil nitrogen, this symptom may be noted even in the cotyledons or seed leaves. In the absence of deep green pigment, or chlorophyll, maximum photosynthetic activity is not attained, which results in a retardation in growth and size of seed leaves, as well as in the subsequent development of the cotton plant.

Long before initiation of reproductive activity by a cotton plant grown under low levels of nitrogen, Wadleigh (51) detected a lower proportion of total nitrogen in its true leaves with an approximate corresponding increase in the proportion of nitrogen in the fruiting branches. Such a relationship is to be expected when nitrogen is limited, since it is the inherent tendency for plants to supply reproductive organs at the expense of vegetative parts. Since nitrogen is a key component of green pigment, or chlorophyll, the color grows less intense, commencing in the lower-most leaves and progressing upward on the plant, as translocation of reserves of this nutrient to the fruiting forms increases. As the chlorophyll disappears, the yellow pigments normally masked by the green become visible and increasingly evident in the leaf which is greatly reduced in size. A typical leaf from a nitrogen-deficient plant is contrasted with a normal leaf in plate 1.

Disorganization of the leaf cells which eventually follows a severe shortage of nitrogen often is accompanied by a development of red pigments known as anthocyanins. Eventually the leaf turns brown and dies, and finally it falls to the ground. This premature discoloration and eventual shedding of leaves, often confused with early maturity, is thus attributable to an inadequate level of nitrogen within the cotton plant.

STALK SYMPTOMS

Nitrogen-deficiency symptoms in cotton are characterized by relatively meager vegetative growth which becomes recognizable very early in the life of the plant. Even before the true leaves make their appearance, an inadequacy of soil nitrogen results in a general lack of vigor and otherwise retarded growth of the plant stalk. Short, stunted, and sparsely-

Courtesy of Alabama Agricultural Experiment Station

Figure 1. Effect of adequate nitrogen on the growth of the cotton plant. Note the development of many vegetative and fruiting branches.

branched plants of a woody texture subsequently develop. In marked contrast, plants which receive an adequate supply of nitrogen remain succulent, grow rapidly, and become profusely branched. The vigorous growth habit of a cotton plant which receives adequate nitrogen is shown in figure 1. The restricted growth habit of a cotton plant which receives an inadequate supply of nitrogen is shown in figure 2. The plot comparison in plate 2 vividly portrays the marked differences in growth herein described.

Whereas cotton plants highly deficient in nitrogen failed to produce any lateral vegetative growth, Wadleigh (51) determined that from two to five vegetative branches developed on those plants to which he had

supplied adequate nitrogen. An adequate vegetative framework was thereby provided for vastly increased photosynthetic activity of the leaves, and thus greater carbohydrate production.

FRUIT SYMPTOMS

In discussing the development of a given fruiting branch, Wadleigh pointed out that a flower bud, in reality a terminal bud, normally occurs at each node. Further elongation of the fruiting branch thus arises from a lateral bud. The extent of growth of the fruiting branch, hence the number of fruiting forms which develop, was determined by Wadleigh to be dependent upon the nitrogen supply available to the plant. The probability that each successive bloom on a branch will set and develop fruit (bolls) is predetermined by the nutritional demands in relation to nitrogen supply of the bud originally initiated.

Courtesy of Alabama Agri. Exp. Sta.

Figure 2. Effect of nitrogen deficiency on the growth of the cotton plant. Note the development of only a few vegetative and fruiting branches

Fruiting charts prepared by Wadleigh revealed that cotton plants with low nitrogen reserves produced, as an average, approximately 20 blossoms, with no flowers beyond the third node of a given fruiting branch. Early abortion or shedding of terminal buds of fruiting branches followed closely, which definitely curbed initiation of additional "squares"—buds and inclosing bracts. Any additional squares that happened to develop beyond the third node were shed. Wadleigh further determined that when the low-nitrogen cotton plants had set a total of five bolls, as an average, all additional young bolls fell off.

Plants grown at the highest level of nitrogen studied, on the other hand, produced approximately three times as many blossoms and set more than four times as many bolls. Wadleigh also found that 90 percent of the bolls which set on plants highly deficient in nitrogen occurred at the primary nodes of the fruiting branches, whereas only 50 percent were so located on plants which had received adequate nitrogen. In other words, flowers and eventually bolls developed further

outward on the fruiting branches of plants supplied with adequate nitrogen, with the result that yields were greatly increased.

According to Wadleigh's data, 60 to 70 percent of the blossoms produced by cotton plants, regardless of the level of nitrogen studied, were shed. Thus, the abscission process in cotton acts as a "safety valve" in that all fruiting forms are shed which cannot be adequately developed at the current level of available nutrients. This is consistent with the usual observation that cotton normally produces many more flowers than it can mature into fruit.

Wadleigh also determined that nitrogen nutrition exerts a determinative effect as to which fruiting branches bear the major portion of the flowers and set bolls. He found that 70 percent of the bolls set on nitrogen-deficient plants were carried on the first 5 fruiting branches which bore 98 percent of the blossoms. In effect, the nitrogen-deficient plants produced only a "bottom" crop of bolls. On bolstering the nitrogenous reserve of the plant, however, an increasing productiveness of the upper branches resulted. Some bolls, for instance, were set above the twentieth fruiting branch of plants supplied with adequate nitrogen, which resulted in the production of a "top," "middle" and "bottom" crop. In the light of these investigations, Wadleigh stated that fruiting behavior in the cotton plant is definitely a function of the amount and quality of available nutrients rather than of water supply to which some investigators have attributed the shedding of fruiting forms.

A further deduction may be made from Wadleigh's results that the difference in number of seeds per boll initiated by plants low or high in nitrogen is not significant. In plants deprived of adequate nitrogen, however, a marked decrease in the number of seeds which developed per boll, with a resulting increase in the number of aborted embryos, or motes, occurred as the fruiting season progressed. In plants which received adequate nitrogen, more sound seeds developed per boll. Embryo abortion obviously limits weight of seeds, hence affects boll size. Wadleigh thus reported that nitrogen nutrition tended to increase boll size.

The average weight of individual seeds tended to increase with an increase in level of nitrogen nutrition, accompanied by a marked increase in protein content. Seeds produced by low-nitrogen plants were found to be only 17.6 percent protein, whereas seeds from high-nitrogen plants contained 27.0 percent protein. The oil content, as determined by Wadleigh, was 29.2 percent in seed from plants inadequately supplied with nitrogen as compared to 24.1 percent in seed from plants receiving

adequate nitrogen. An increase in both number and size of bolls resulting from adequate nitrogen, however, should result in more total oil being produced per acre.

Lint percentage, according to Wadleigh's observations, also tended to decrease with an increase in nitrogen supply to the plants. He ascertained by several different criteria of measurement, however, that length of lint showed a slight tendency to increase with increase in the levels of available nitrogen.

These findings led Wadleigh to conclude that a definite relationship exists between growth of cotton plants, as indicated by vegetative vigor, and yield of lint and seed. This expected relationship, he further concluded, is frequently disturbed by the ravages of insects and diseases. Yet the fact remains that small, stunted plants do not constitute a framework of sufficient size to produce a bumper crop of cotton.

PHOSPHORUS (P) DEFICIENCY

Although required by cotton in a lesser quantity than nitrogen, a rather substantial amount of phosphorus must be supplied the crop to realize optimum yields. This nutrient is known to stimulate early and extensive development of the root system which, in turn, enables the plant to grow rapidly and to mature earlier. The presence of this nutrient is essential to such processes as photosynthesis, synthesis and breakdown of carbohydrates, and transfer of energy which take place in the plant. As a component of cell cytoplasm, or living matter, phosphorus is involved in the division of cells and transfer of hereditary characteristics. Phosphorus also stimulates blooming and promotes seed formation by the plant.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Lack of phosphorus long since has been known to constitute a limiting factor in cotton production even in virgin soils of the humid climates which contain a low native supply of this element. Furthermore, the relatively low pH value in many of these soils indicates that soil complexes exist which can lock up or "fix" large quantities of the phosphorus that may be applied in soluble form. Fixation in the soil rather than loss from the soil, as is the case with nitrogen, is the chief problem relating to phosphorus.

Unquestionably the calcium content of the carriers or fillers in fertilizers, though often highly inadequate for creating the most desirable pH level in the soil, has lowered somewhat the fixation of applied

phosphorus, and thereby favored yields in the old Cotton Belt of the South. Raising the pH of those soils to appropriate levels through the application of agricultural lime is thus suggested to increase the efficiency of applied phosphorus and thereby lower the incidence and degree of deficiency symptoms.

With the native supply of phosphorus becoming progressively greater from the eastern to the western areas of the Nation, deficiencies of this nutrient decrease proportionately in going from the old Cotton Belt to the newer areas of production. Furthermore, fixation of applied phosphorus is a problem of lesser importance in the highly calcareous soils of the semi-arid Southwest and West on which production of cotton has been rapidly expanding.

LEAF SYMPTOMS

Leaves from phosphorus deficient plants, in marked contrast to leaves from nitrogen deficient plants, remain dark green in color. Similarly, however, they are reduced in size. A comparison in both size and color of a typical leaf from a phosphorus deficient plant with one from a nitrogen deficient plant is shown in plate 1. The two leaves, in turn, are compared with a leaf from a plant which was adequately supplied with both nutrients.

As is the case with a shortage of nitrogen, too little phosphorus is first reflected in the lower or older leaves of the cotton plant. The deepening of the green color of the leaves then progresses upward on the stalk to the extent that phosphorus is deficient. This occurrence suggests that the nutrient moves, as the supply diminishes, from the older tissues to and in support of the younger tissues.

STALK SYMPTOMS

Other than the dark green color and reduced size of the foliage, a most striking phosphorus deficiency sympton is the decidedly dwarfed condition of the cotton plant. The marked difference between size of plants which received adequate phosphorus and those grown on a soil highly deficient in this element is shown in plate 3.

As will be noted in the mid-season stage of growth of cotton shown in plate 3, the primary stalk of a phosphorus deficient plant is severely restricted in size. Practically no secondary branches are to be seen. The ability of the plant to produce carbohydrates, as well as set the number

of bolls required for optimum yields, is thereby greatly reduced. Both total growth and eventually yield are thus reduced under deficiencies of phosphorus.

FRUIT SYMPTOMS

An extreme deficiency of phosphorus not only reduces the number but also delays maturity of the relatively few cotton bolls which actually develop. First blooms may be observed on highly deficient plants

Figure 3. Effect of phosphorus deficiency on maturity of cotton. Plants in plot at left, which received no phosphorus in the fertilizer, show typical late maturity. Plants in plot at right, which received adequate phosphorus in the fertilizer, show normal maturity.

at a time when fully developed and opened bolls occur on plants grown similarly but adequately supplied with phosphorus. This occurrence is strikingly shown in figure 3.

This delay in blooming, fruiting, and final maturity of bolls caused by a deficiency of phosphorus can present a very serious problem where the infestation of boll weevils is likely to be heavy. Even in the absence of insect damage, failure of bolls to fully develop before the normal maturity date is likely to occur. Inferior quality of staple, as well as reduction in number of bolls and thus quantity of seed and lint, often results from a phosphorus deficiency in the cotton plant.

POTASSIUM (K) DEFICIENCY

A substantial quantity of potassium, as the third major nutrient, likewise is required for optimum production of cotton. The capacity of the cotton plant to accumulate calcium very probably tends to intensify the need for potassium to maintain an adequate supply of soluble carbonate ions. These ions are necessary in the synthesis of constituents required in the production of the carbonaceous fibers for which cotton is primarily grown. Also, potassium is necessary for movement of starches and sugars between different parts of the plant, for normal cell division and growth, and for the neutralization of organic acids. Furthermore, potassium is known to increase the oil content of cotton seeds.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

A definite interrelation exists among potassium, calcium, and sodium in the nutrition of the cotton plant. The accelerated use of limestone in some areas very probably has significantly increased the intensity of potash deficiency symptoms in cotton. This may be partially due to the lowering of the availability of the soil potassium through the formation of low solubility compounds, and partially due to the increased quantity of calcium absorbed which, in turn, increases the requirement of potassium for optimum production. Potash deficiency symptoms, therefore, are most likely to occur in soils with abundant supplies of calcium, particularly if the vegetative growth of cotton plants is restricted and fruiting is unusually heavy.

Although sodium has not been determined an essential nutrient in the growth of the cotton plant, research has established that this nutrient in a soil relatively low in potash will result in both growth response and increased yield. According to established solubility values, however, potassium should be much more efficient than sodium in maintaining a soluble supply of carbonates available for photosynthesis. The fact remains, however, that the presence of sodium in the soil seems to partially alleviate potash deficiency symptoms in cotton plants grown under low levels of potash.

LEAF SYMPTOMS

The symptoms in cotton associated with lack of potassium in fertilizer often are very pronounced. A lack of this nutrient results in a striking malnutrition symptom commonly called "cotton rust." The first symptom, a yellowish-white mottling of the foliage, changes the

leaf color to light yellowish-green, yellow spots appearing between the veins. The centers of these spots die and numerous brown specks occur at leaf tips, around margins, and between veins. The tips and margins break down first and curl downward. Leaves from a highly deficient plant showing the earlier signs of potash hunger are contrasted with a normal leaf in plate 4.

As the physiological breakdown progresses, the whole leaf becomes reddish-brown, dries, and finally becomes scorched and blackened in appearance by the time it is prematurely shed. Premature dropping of

Figure 4. Cotton showing potassium-deficiency symptoms. Plot at right received no potash. The leaves shed prematurely and the bolls were dwarfed. Plot at left received a complete fertilizer containing adequate potash.

leaves from potash deficient plants, in comparison to retention and continued activity of those on non-deficient plants, is quite evident in figure 4.

STALK SYMPTOMS

The cotton stalk often fails to develop to its full potential when a deficiency of potash limits carbohydrate production. Long before its normal maturity date, the main stem and branches often become withered and dry. In contrast, a plant supplied with adequate potash continues its vigorous growth until normal maturity is reached, as evidenced in plate 6.

FRUIT SYMPTOMS

The premature shedding of leaves resulting from potash deficiency prevents the normal development of bolls which remain dwarfed and immature. Many bolls so affected fail to open altogether, or only partially, and the fiber therein is of poor quality. A boll from a plant which was highly deficient in potash is compared with one from a plant which received an adequate supply of this nutrient in plate 5. As may be expected, the picking of seed cotton from improperly developed bolls of potash deficient plants is much more difficult and far less complete than from bolls which have developed fully and matured normally.

CALCIUM (Ca) DEFICIENCY

The relationship of calcium to soil pH, and the importance of proper soil pH to crop production, are subjects that are far too complex and much too complicated to come within the scope of this chapter. Other than to mention the importance of maintaining a desirable soil reaction for maximum availability of other plant nutrients, which proper applications of limestone can effect, this discussion will be limited to the contained calcium as an essential nutrient in the normal growth of the cotton plant. Calcium is required within the plant cell to favorably influence the activities of certain enzymes. It is especially essential in cementing together the walls of cells to create the form and shape which the individual plant assumes. When calcium and pectin combine, calcium pectate results which is the cementing material of cell walls. These facts point up the essentiality of calcium in the growing points of roots and shoots of plants where division and formation of new cells take place.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Considered generally, upland soils of the old Cotton Belt are deficient in calcium. Limited out-croppings of calcareous soils occur, however, throughout the South. Quite frequently cotton plants grown on these soils, in comparison to those grown on nearby highly acid soils, reflect the significant effect which calcium has upon the vegetative and fruiting habits of the crop. A low supply of calcium results in the production of relatively large plants and comparatively few fruiting forms. In comparison, an abundant supply of calcium results in the production of relatively smaller plants but stimulates early and abundant fruiting.

Since cotton is a calcium-accumulator, considerable variation may occur in the calcium content of plants without significant effects upon

growth and yield. Since the total quantity of calcium absorbed by a plant may be significantly affected by its capacity to synthesize organic acid compounds, a fairly uniform calcium content may be found in plants grown on soils differing widely in calcium content.

SYMPTOMS

Since the calcium content of cotton seeds has been determined to be very low, investigators have suggested that the intensity of the energy available to seedling plants from respiration may not be sufficient to readily assimilate phosphorus in the form of calcium phosphate. As soon as cotton seedlings emerge from the ground and are capable of

Figure 5. Three-week-old greenhouse cotton seedlings grown in complete nutrient solution low in calcium (8 p.p.m.). Note the bending and the collapse of the leaf petioles.

Courtesy of John T. Presley, Mississippi Agricultural Experiment Station

utilizing the energy of sunlight, which contains a higher level of energy than commonly is available in respiration processes, need arises for an abundant supply of calcium. In the absence of an adequate supply of calcium at that time, deficiency symptoms are likely to appear.

Three-week-old cotton seedlings which show calcium deficiency symptoms are illustrated in figure 5. The plants pictured were grown in a complete nutrient solution containing 8 parts per million of calcium. Note the bending and the beginning of the collapse of affected leaf petioles. These symptoms manifest themselves in the cotyledons, as well as in the true leaf petioles. Loss of stands from the dying of cotton seedlings during cool, wet seasons may possibly be related to an inadequate supply of available calcum prevailing at the time. The inherited calcium-tolerance mechanism may result in the synthesizing by cotton seedlings of organic acid compounds which must be partially neutralized to produce vigorous growth.

MAGNESIUM (Mg) DEFICIENCY

Magnesium is another nutrient element that is used by cotton in rather appreciable amounts. This nutrient has been determined to be active in enzyme systems, but more especially is it significant as a constituent of chlorophyll. As such, magnesium plays a vital role in the photosynthetic process which takes place in the plant.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Magnesium deficiency symptoms appear rather widespread in the southeastern part of the United States, including most of the Coastal Plain, some of the Piedmont, the Ozark Plateaus, and the southern end of the Appalachian Highland. Deficiencies appear much less frequently on the red podzolic soils of the South that usually contain considerable quantities of this nutrient which may become available to a long-growing-season crop like cotton.

The kinds and quantities of fertilizers added to the soil often have a very significant effect upon the occurrence and the extent of magnesium-deficiency symptoms in cotton. The solubility of the magnesium compounds in fertilizers has been related directly to the incidence of deficiency symptoms in the cotton plant. The source of nitrogen in the fertilizer used, for instance, has been found to exert a pronounced influence on the solubility and loss of magnesium from soils. Where ammonium phosphate has been used as the source of nitrogen, as an

example, magnesium deficiencies have been held at a minimum. This has been ascribed to the formation of magnesium ammonium phosphate, the slight solubility of which prevents the leaching of large quantities of magnesium from light-textured soils. In contrast, symptoms have been far more frequent where fertilizers containing large amounts of nitrate, sulphate, or chloride ions were added to such soils. Occurrence of marked magnesium deficiency symptoms in cotton has been almost completely eliminated on soils which have received sufficient amounts of dolomitic limestone applied as such, or introduced into the soil as a component of fertilizers.

SYMPTOMS

The characteristic symptom of magnesium deficiency in cotton is purplish-red leaves with green veins, as shown in plate 7, in which such leaves are compared to a normal leaf. Late in the season, however, it is sometimes difficult to distinguish between the color due to magnesium deficiency and that due to aging or maturity, though the latter is apt to be orange-red rather than purplish-red.

Magnesium deficiency symptoms appear first on the lower leaves of cotton as shown in plate 8. As the leaves die, they are shed prematurely. Loss of leaves, with a corresponding reduction in photosynthetic activity, results in failure of the vegetative plant, as well as the fruiting forms borne thereon, to develop to their maximum potential. Yields of both fiber and seed may be greatly reduced thereby.

SULPHUR (S) DEFICIENCY

Cotton is among those crops which utilize relatively large amounts of sulphur. This is to be expected since cotton seed is rich in protein, one constituent of which is sulphur. In addition, as is the case in all other plants, sulphur is associated with the formation of green pigment, or chlorophyll, and thus affects carbohydrate metabolism. Furthermore, certain of the hormones which serve as growth regulators in plants are known to contain sulphur.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Although the sulphur supply is rather meager in certain cotton soils, production of the crop has been satisfactorily maintained in the past through a replenishment from one or a combination of sources, namely air, irrigation water, and conventional fertilizers.

In areas surrounding heavy industrial activity, the sulphur released

during the burning of coal may be returned to the soil in rainwater at a rate as great as 40 pounds per acre annually, an amount usually sufficient for a high-yielding cotton crop. In non-industrial localities, however, sulphur additions from rainwater are far less significant, since only 4 pounds per acre per year, as an average, are returned to the soil. This amount is inadequate, of course, for a good yield of cotton. Depending on the source and amount applied, irrigation water likewise supplies varying amounts of sulphur to the soil. As a third source of replenishment, certain conventional fertilizers, particularly superphos-

Courtesy of F. L. Davis, Louisiana Agricultural Experiment Station

Figure 6. Effect of sulfur deficiency on growth of cotton. The plot on the right received no sulfur in the fertilizer.

phate, used in past years have supplied rather substantial quantities of sulphur for the production of cotton.

Under the growing trend toward the use of fertilizers containing higher concentrations of major nutrients, from which some or all of the sulphur is eliminated, cotton growers are resorting to a planned program of adding sulphur compounds to the soil. Rather than rely on the incidental applications of sulphur contained in fertilizers, which may be entirely inadequate, full requirements of the cotton crop are thereby being assured.

SYMPTOMS

When cotton is grown on a soil deficient in sulphur, new leaves at the tops of plants become yellower as growth progresses, whereas the

old leaves usually remain green. This characteristic symptom of sulphur deficiency may be noted in figure 6, in which a plot comparison of cotton plants receiving inadequate and adequate sulphur are pictured. This is in marked contrast to the pattern of yellowing in nitrogen deficiency which almost always begins with the older leaves at the bottom of the plant and proceeds upward on the stalk. This difference has been attributed to the fact that unlike nitrogen, sulphur is not readily translocated to new growth.

In other respects, symptoms of sulphur deficiency are similar to those which result from an inadequate supply of nitrogen. Sulphur deficient plants are characteristically small and spindly with short, slender stalks. A general retardation in growth becomes quite apparent in cotton plants growing on soils highly deficient in this nutrient. The generally dwarfed plants resulting from a deficiency of sulphur produce fewer vegetative and fruiting branches, as noted in plate 9, than plants which have received adequate sulphur. In the sulphur deficient plant pictured, the characteristic yellow leaves in which the veins remain dark green can be noted. A deficiency in sulphur, unlike a deficiency in nitrogen, does not result in the cotton plant being any less fruitful for its size. Yet the fact remains that total yields are decreased as a result of the plants being smaller, and failure of bolls to reach their potential size.

BORON (B) DEFICIENCY

Even though required in trace amounts, this nutrient plays a highly important role in the reproductive processes of the cotton plant. Furthermore, boron influences conversion of nitrogen and carbohydrates into more complex substances such as proteins, affects the transfer of sugars within the plant, exerts a marked influence on cell division, and aids in the formation of certain membranes.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

The greater part of the old Cotton Belt has been designated as an area in which boron deficiency will become more widespread in the immediate future. On highly calcareous soils or heavily limed soils, supplies of available boron may be reduced to very low levels and thereby result in reduced yields of cotton. The calcium from limestone combines with soluble boron to form calcium metaborate. With the continuing increase in the application of agricultural lime in the old Cotton Belt, a significant decrease in solubility and availability may reasonably be expected.

The very low solubility of calcium metaborate, as compared to the high solubility of potassium tetraborate, may be one of the reasons why increasing the available calcium in the soil decreases the availibility of the boron present. By the same token, the high solubility of potassium tetraborate suggests that the addition of potassium should increase the availability of the boron in the soil. This possibility may be responsible for some of the increases associated with potash applications. Since many of the soils in the old Cotton Belt require an application of lime to produce optimum yields of cotton, a simultaneous application of boron necessarily may be required.

Since boron occurs in both the mineral form and in the soil organic matter, deficiencies may be expected in soils which have a low mineral level or are low in organic matter. Such is the case with many soils within the old Cotton Belt. Extreme drought, therefore, may result in lower availability of boron normally made available through the breakdown of organic matter.

SYMPTOMS

Boron-deficiency symptoms frequently appear first in the terminal growth of the cotton stalk. The terminal bud often dies, checking linear growth. Many lateral branches then arise which have short internodes and enlarged nodes. These impart a bushy appearance to the plant, which is often referred to as a rosette condition. The characteristic tendency of boron deficient plants to assume the rosette, or profusely branched condition, may become evident, even in the young stages of growth. Young leaves of boron deficient plants frequently are yellowish-green in color.

Miley and Woodall of Arkansas (33), and Lancaster et al. of Mississippi (29), have described certain boron-deficiency symptoms in cotton which are appearing rather widespread in their respective states during the growing season under certain climatic conditions. As related, the darker green, older leaves often become thick and leathery and frequently have abnormally long, spongy petioles. The shorter leaf petioles often are twisted with small ruptures appearing over their surfaces. The pith within the leaf petiole may become discolored. Late in the growing season, leaves on the upper half of the plant are either irregularly lobed, ragged-edged, or distinctly small in size. These leaves usually remain green until the date of killing frost.

At a low boron level, flower buds become chlorotic, and the bracts flare open. Rupturing usually occurs at the base of the square either

inside or outside the bracts. An excessive flow of plant juices from the fruit and leaf nectaries frequently occurs. Finally, many of the fruiting forms, both squares and young bolls, become dried out and either remain on the stalk or fall to the ground. In plate 10 is pictured a field view which reveals the heavily fruited plants which received adequate boron and the practically barren plants which failed to receive adequate boron. Two contrasting plants, also shown in plate 10, reflect these characteristics in greater detail.

In association with a boron deficiency, bolls which survive often are deformed, presenting a flat-sided or hook-billed appearance. Such bolls are reduced in size and tend to open only partially. A dark discoloration which extends inside may be noted at the base of the boll. The excessive shedding of both squares and young bolls, together with the deformed condition of the relatively few which may persist, results in extremely low yields.

If a soil is near a deficiency level of available boron, a heavy lime application will hasten the appearance of deficiency symptoms. This emphasizes the importance of applying lime according to soil test. There remains the further problem of determining the quantity of boron that may be applied without leading to toxicity. In areas where boron deficiencies are occurring in cotton, the safe levels of boron application are being determined through carefully controlled experiments.

MANGANESE (Mn) DEFICIENCY

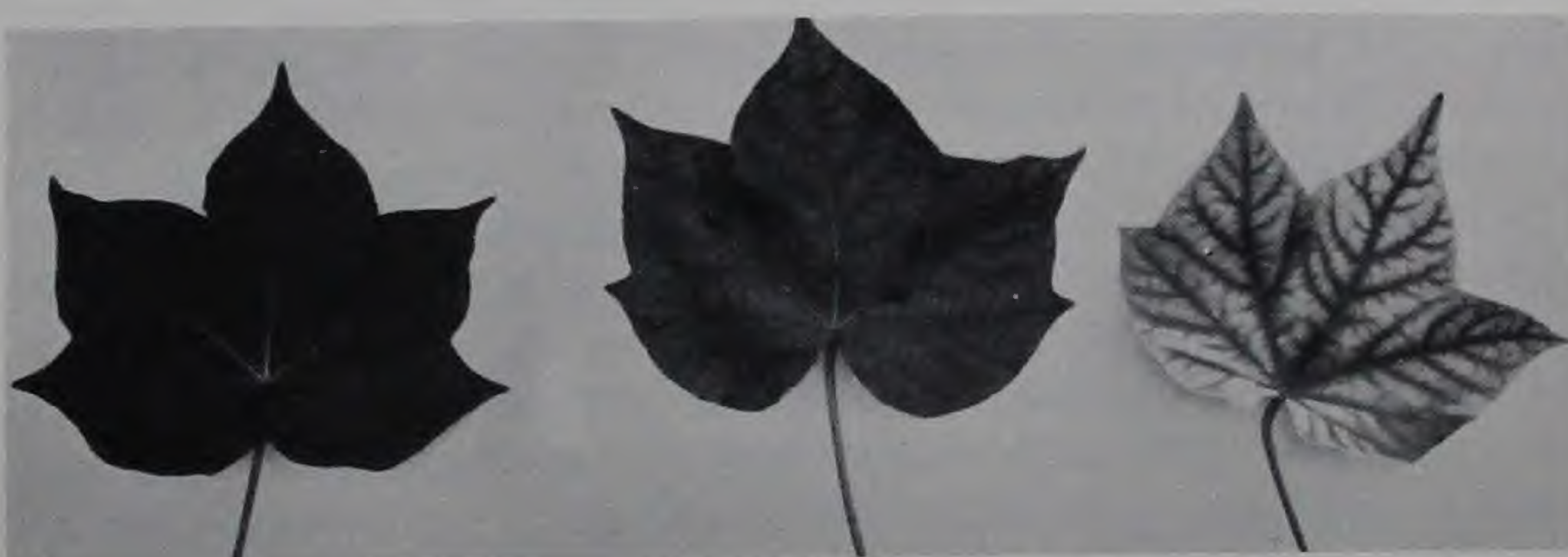
The minute quantity of manganese essential to optimum production of cotton is thought to influence the movement of iron within the plant. In conjunction with iron, this nutrient apparently assists in the synthesis of chlorophyll. This theory is based on the fact that all chlorophyll tissues (leaves) have high concentrations of manganese.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Manganese deficiency symptoms in cotton have not been widely observed under field conditions. This nutrient can be leached from soils, however, particularly under highly acid conditions, with the result that deficiency symptoms may appear in crops grown thereon. As an example, certain low pH soils along the Atlantic Coast in the southeastern states, which originally contained low native amounts of manganese, are now deficient in this nutrient. Deficiency symptoms which did not appear earlier, due to the strongly acid reaction of the soils which

favored maximum availability of the limited quantity of manganese, are now manifesting themselves in cotton grown in those areas.

The liming of acid soils to an alkaline reaction has been the most common cause of manganese deficiencies in crops. The relatively low solubility of manganese hydroxide, which often prevails under such conditions, indicates how the availability of the contained manganese may be significantly lowered through liming. The problem of manganese deficiency may thus be solved, depending on the soil reaction, either through direct application of manganese, or through the application of sulphur or other acid-forming materials which increase the solubility and availability of native supplies of this element. In some



Courtesy of New Jersey Agricultural Experiment Station

Figure 7. Left, normal leaf. Right, manganese-deficient leaves

cases, manganese sulphate applied as a spray on the foliage of certain crops has successfully eliminated deficiency symptoms.

SYMPTOMS

Manganese apparently tends to accumulate in the leaves of plants. In the absence of adequate quantities of this nutrient, the upper or younger leaves are the first to be affected. They become yellowish-gray or reddish-gray in color with green veins. The characteristic deficiency symptoms in cotton grown in solution cultures at the New Jersey Agricultural Experiment Station are shown in figure 7, in which two stages of manganese deficiency in leaves are contrasted with a normal leaf of a cotton plant which received an adequate supply of this nutrient.

Excessive quantities of water-soluble manganese in the soil have been reported by Neal and Lovett (38, 40). The first noticeable feature is the appearance of abnormal leaves. They are puckered, mottled, partially chlorotic, and variously distorted in early stages, with necrotic lesions

subsequently appearing along and between the veins. As the plant approaches maturity, the affected leaves become slightly thickened, brittle, and ragged at the margins as illustrated in figure 8. This condition has been termed "crinkle leaf" in cotton.

Very probably various degrees of manganese toxicity occur in cotton grown on many of the highly acid red podzolic soils of the old Cotton

Figure 8. Crinkle leaf or manganese toxicity of cotton. A, healthy plant. B to D show varying degrees of manganese toxicity symptoms. The leaves are puckered, mottled, partially chlorotic and variously distorted.

Courtesy of D. C. Neal, U. S. Department of Agriculture

Belt. More definite information is needed concerning the quantities of manganese required for optimum growth, as well as the level at which this nutrient will become toxic to the cotton plant.

ZINC (Zn) DEFICIENCY

That the level of zinc in certain soils of the nation is inadequate for maximum crop production long has been established. Particularly in regions in which intensive cropping programs are followed on strongly-weathered and coarse-textured soils, as in certain sections of Florida, zinc has constituted a limiting factor in crop production. In other areas, low availability rather than limited total zinc supply has resulted in the

appearance of zinc deficiency symptoms in growing crops. Heavy use of agricultural lime on acid soils raises the pH with the resulting formation of zinc hydroxide which has very low solubility. The insolubility of zinc phosphates also suggests that large applications of phosphorus also may tend to decrease the availability of zinc to plants.

In the Southwest and West where land-leveling is widely practiced to set the stage for high yields through more effective irrigation, as well as through better drainage and more uniform cultivation and application of pesticides, the incidence of zinc deficiency in cotton is increasing on some soils.

INFLUENCE OF SOIL AND CLIMATIC CONDITIONS

Appearance of zinc deficiency following land-leveling may reasonably be expected to occur, according to Krantz and Brown (27), since the available zinc of the surface soil is often double that of the subsoil. As stated by Krantz, this may be attributed to the fact that zinc is held by the soil particles, and does not move downward with irrigation water. Deep cuts into a soil that is moderately low to low in available zinc may well expose zinc-deficient subsoils. Over those somewhat localized areas of exposed subsoil in a given field, cotton is likely to exhibit zinc deficiency symptoms.

SYMPTOMS

As described by Bassett (1), young, affected plants fail to develop normally. Stalk elongation practically ceases for a while, the shortened internodes imparting a bushy appearance to the young plants. Growth usually is renewed later in the season, however, with rapid development of stems and leaves. By the end of the season, the plants may be fairly rank.

Bassett also observed that germination of cotton seeds usually is normal under zinc deficient conditions. Shortly after the appearance of the first true leaves, a general bronzing and often a pronounced interveinal chlorosis appears. The leaves become thick and brittle with their margins cupped upward, as shown in plate 11.

Squares and flowers may develop on young zinc deficient plants before retardation of growth commences, but these usually are shed. After growth is renewed, additional squares may be set which mature into bolls depending on climatic conditions. An extremely late crop results which is always hazardous from the viewpoint of both insect and weather damage. In any event, yields are drastically reduced as the result of

losing the earlier and usually more valuable bottom crop of seed cotton. These characteristic departures in growth from that of a plant which receives adequate zinc also are pictured in plate 11.

SUMMARY

In view of the wide diversity of soil types and climatic conditions under which cotton currently is produced, no attempt will be made to suggest rates of application of the several essential nutrients that will eliminate the deficiency symptoms ascribed to each. The suggestion is made instead that all diagnostic tools, such as soil and plant tissue tests, be employed and related to information established through research in an effort to remove as nearly as possible any guess work in the fertilization of the crop. Since the relative cost of commercial plant nutrients is among the lowest of all production items, the grower can not afford to permit a deficiency to constitute a limiting factor in the production of cotton.

Although the essentiality to plant growth of chlorine, copper, iron, and molybdenum has been firmly established through research, deficiency symptoms of these have not been clearly differentiated and fully described for cotton. For this reason, these nutrients are not discussed in this chapter, nor are they included in the key to follow in which the better established deficiency symptoms are identified.

KEY TO PLANT NUTRIENT DEFICIENCY SYMPTOMS IN COTTON

I. Causal parasites or viruses absent . . . . common to all deficiencies.

II. More or less localized effects and decreased growth . . . . . . common to all deficiencies.

Element Deficient

A. Effects localized on older or lower leaves or more or less general on whole plant.

B. Symptoms local, occurring as mottling or chlorosis with or without necrotic spotting (areas of dead tissue) on lower leaves; little or no drying up of lower leaves.

C. Lower leaves brittle, curved or cupped under, with yellowish-white mottling between veins. Necrotic spots present . . . . Potassium

C. Lower leaves purplish-red with green veins . . . . Magnesium

B. Symptoms general, with yellowing and drying, or "firing," of lower leaves.

C. Plants light green; lower leaves yellow, drying to brownish color . . . . Nitrogen

C. Plants dark green, leaves and plants small, maturity delayed . . . . Phosphorus

C. Pronounced interveinal chlorosis and bronzing of leaves which become brittle with upturned margins; maturity delayed . . . . . Zinc

A. Effects localized on terminal growth (newer or bud leaves).

B. Dieback involving terminal buds, resulting in many-branched plant. Young leaves yellowish-green, flower buds chlorotic. Early indications are banded petioles and ruptured peduncles . . . Boron

B. Terminal buds remain alive; chlorosis of upper or bud leaves.

C. Leaves yellowish-gray or reddish-gray with green veins . . . . Manganese

C. Young leaves first affected, turning pale green, older leaves remaining greener; plants dwarfed . . . . Sulphur

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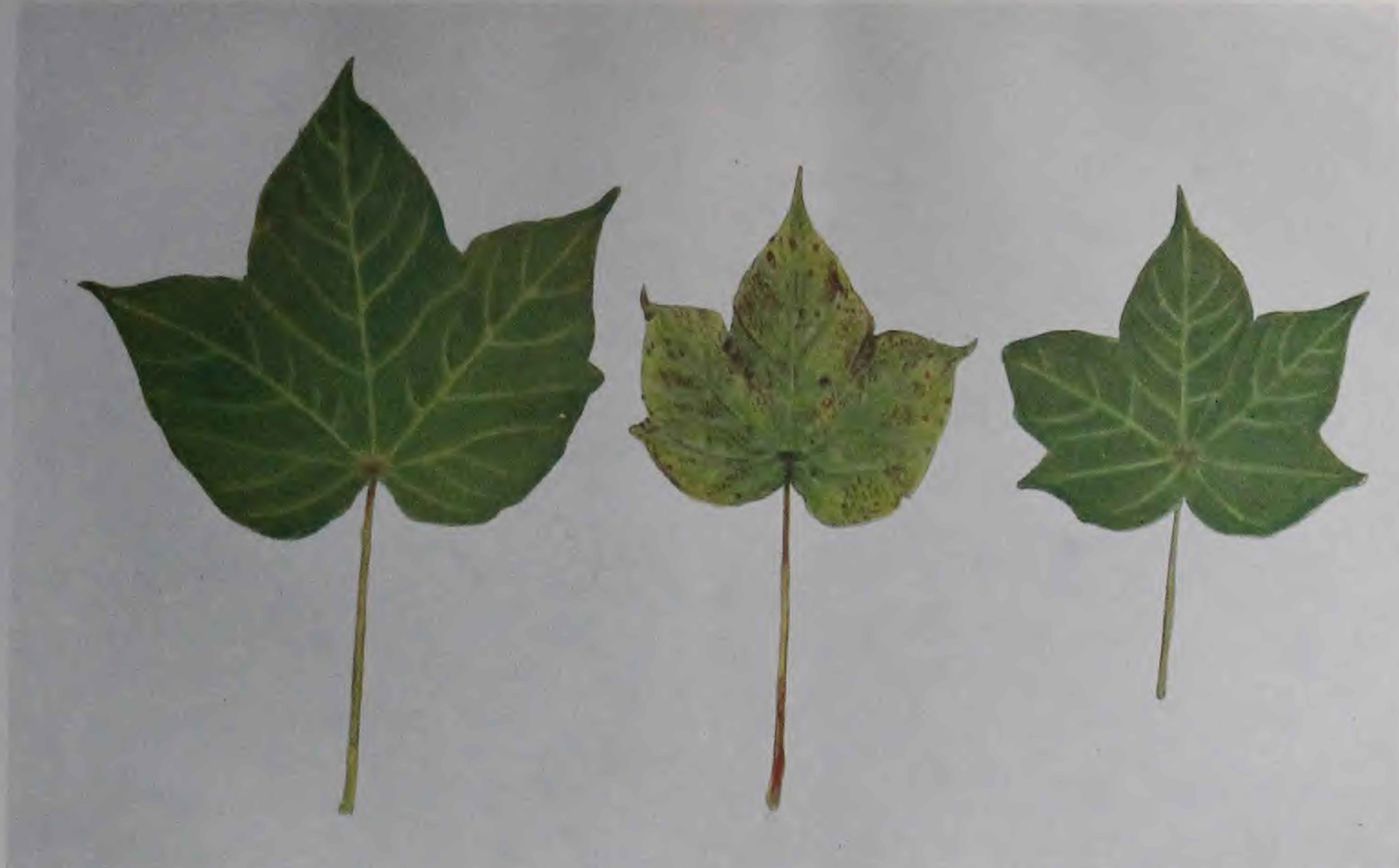
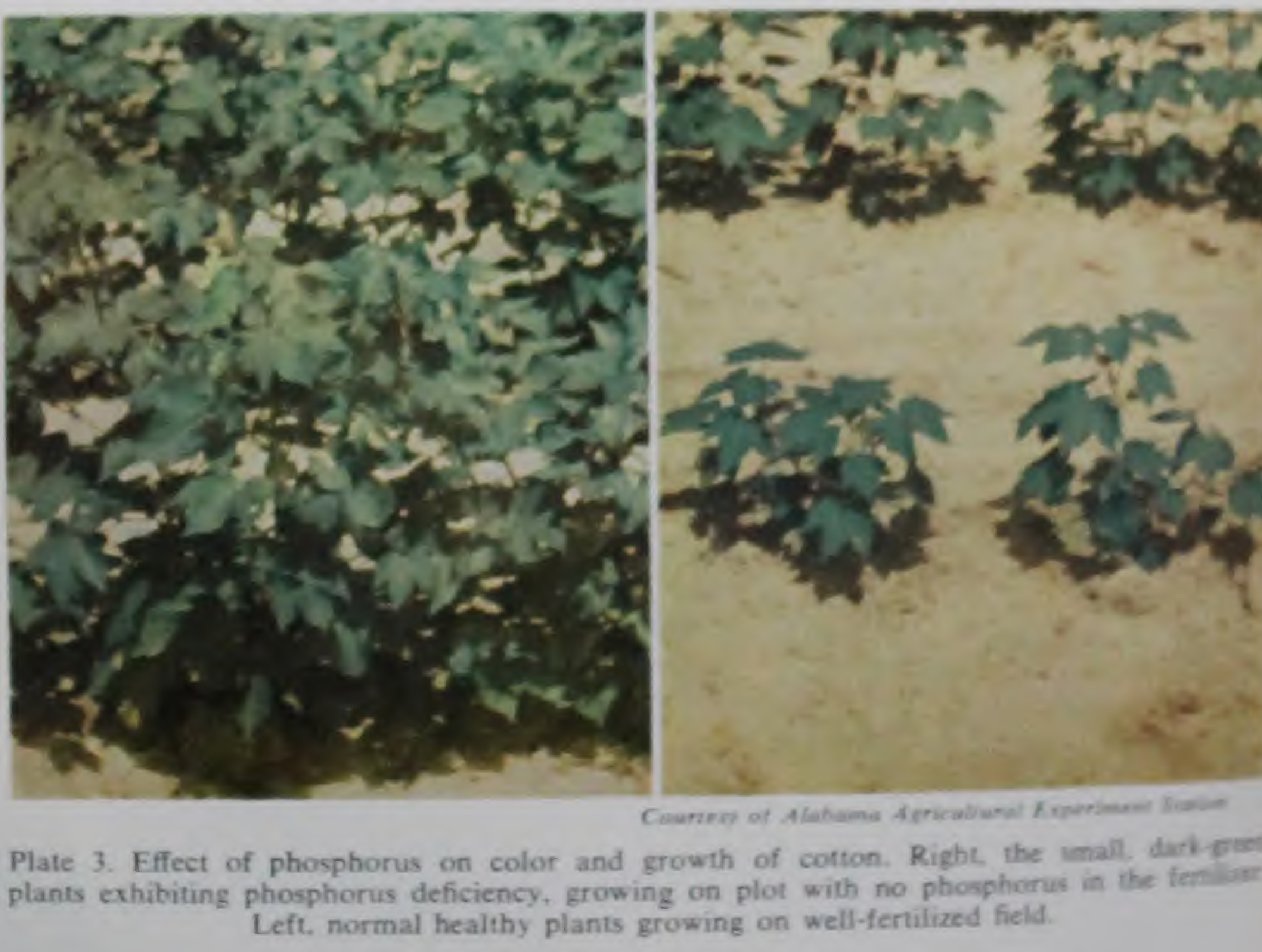


Courtesy of Alabama Agricultural Experiment Station

Plate 1. Cotton leaves showing normal condition and nitrogen and phosphorus deficiency symptoms. Left, normal green color. Center, yellowish-green color due to nitrogen deficiency. Right, dark-green color characteristic of phosphorus deficiency.

Courtesy of Pee Dee Experiment Station, Florence, S. C.

Plate 2. Nitrogen deficiency in cotton is characterized by yellow color of foliage and slow growth. The plot on the left did not receive nitrogen in the fertilizer; the plot on the right received a complete fertilizer.



Courtesy of Alabama Agricultural Experiment Station

Plate 3. Effect of phosphorus on color and growth of cotton. Right, the small, dark-green plants exhibiting phosphorus deficiency, growing on plot with no phosphorus in the fertilizer. Left, normal healthy plants growing on well-fertilized field.

Plate 4. Cotton leaves showing potassium deficiency symptoms. Left normal green leaf. Right, reddish-brown leaves with ragged margins due to potassium deficiency.

Plate 5. Cotton boll showing potassium deficiency symptoms. Left, normal, large, well-opened boll. Right, small, immature, partly opened boll resulting from a deficiency of potassium.

Courtesy of Pee Dee Experiment Station, Florence, S. C.

Plate 6. Growth characteristics due to potassium deficiency. Top, plants did not receive potash in the fertilizer. Note premature shedding of the leaves and the immature, partly opened bolls. Bottom, normal growth of plants that received a complete fertilizer.

Plate 7. Cotton leaves showing purplish-red color with green veins resulting from magnesium deficiency. Leaf at left is normal.

Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture

Plate 8. These cotton plants did not receive magnesium. Note the purplish-red color of the lower leaves and premature shedding of foliage.

Courtesy of F. L. Davis, Louisiana Agricultural Experiment Station

Plate 9. Sulfur deficiency in cotton. The plant on the right did not receive sulfur in the fertilizer. Note the dwarfed growth and yellow leaves with green veins. These characteristics are similar to nitrogen-deficiency symptoms, though the green color of the veins may be more distinct in the case of sulfur deficiency. The large, normal green plant on the left received sulfur.

Courtesy of W. N. Miley and G. W. Hardy, Arkansas Agricultural Extension Service and Experiment Station, respectively.

Plate 10. *Boron deficiency*. Top: Cotton plants showing mid-season, drought-induced boron deficiency symptoms in untreated plot at left. Delayed maturity of the plants, the branches of some rosetted at their tips, and a sparse set of bolls are readily noted. Normal maturity and a good boll set characterize plants in treated plot at right.

Bottom: Removal of all foliage clearly reveals almost barren boron deficient plants in the untreated plot and heavily fruited plants in the treated plot above.

Courtesy of B. M. Krantz, California Agricultural Extension Service

Plate 11. *Zinc deficiency*. Top: Effect of zinc deficiency in young cotton plants. Note the general yellowing to bronzing between the veins of leaves, the older ones of which are thick and brittle with their margins often cupped upward.

Bottom: Effect of zinc deficiency in older cotton plants at left, which failed to receive an adequate supply. Note the clustering of smaller leaves near the top of the stalk which is bare at its base. Early inhibited growth often results in a late fruit set. Plants at right, which received adequate zinc, display normal growth habits.

Chapter IV

Nutrient Deficiencies in Tobacco

By J. E. McMurtrey, Jr.*

When the soil does not furnish adequate quantities of these chemical elements necessary for the normal development of plants, it becomes a matter of great importance to supply the elements by means of manures or fertilizers. But first some simple, practical method for finding out what elements are lacking must be put to use.

This can be done by careful observation of growing plants, a process which should and does furnish the most direct evidence of their nutritional condition. The tobacco grower who wants a high-quality product should keep his plants growing normally and during growth watch for signs that something is wrong. Careful experimental work has resulted in a systematic method of recognizing or diagnosing shortages of several chemical elements by symptoms produced in the tobacco plant.

Of course, growth of plants can be compared by measuring their dry weight; in fact, this is the method that usually has been followed in experimental work. It is not well adapted to the needs of the farmer, however, and in the case of tobacco it does not by any means tell the whole story. With tobacco, the total tonnage produced is not the only thing of importance. Much of the value of the crop depends on that complex and elusive factor, quality. Quality in turn depends on color, aroma, fire-holding capacity, texture, elasticity, body, ability to improve with aging, and other characteristics. Moreover, the qualities required are different for the several so-called types or classes of tobacco —cigar, flue-cured, burley, Maryland, dark air-cured, and dark fire-cured. Conditions during growth unquestionably influence the quality of the final product, though it is by no means possible as yet to tell exactly in what ways.

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* J. E. McMurtrey, Jr., Leader, Tobacco Investigations, Crops Research Division, A.R.S., U. S. Department of Agriculture, Beltsville, Maryland.

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BACKGROUND OF DIAGNOSIS

According to modern views (12), the higher plants require the following chemical elements in order to make normal growth, and they require these elements in suitable quantities and forms: carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, iron, manganese, copper, molybdenum, zinc, and boron. The importance of silicon and aluminum in the growth of the tobacco plant under field conditions has not been fully determined, though these elements have been reported by some investigators to be of importance in the growth of other plants.

Nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, iron, manganese, copper, molybdenum, zinc, and boron are present in varying quantities in agricultural soils. Sometimes they may be present in abundance but one or more of them may be tied up in chemical compounds that plants cannot readily use. This, of course, is equivalent to a shortage. Decreased growth results when the supply of any one of these elements is insufficient. Since this is true for all of them, it is necessary to watch for other signs besides decreased growth to discover which element is not present in large enough quantities.

These signs or symptoms of mineral hunger in plants, of course, may be modified to some extent by other factors affecting growth. Light, temperature, and amount and distribution of the water supply all have an influence on growth, and they also affect the total quantity of the chemical elements required by the plant and the rate at which these elements must be supplied. Even under varying field conditions, characteristic symptoms due to the deficiency of an element will be found essentially the same.

To say that a single element is deficient is ordinarily the same as saying that there is an excess of other elements in relation to that one. The result is an unbalanced nutritional condition in the plant. It may not always be possible to distinguish between the effects due to the deficiency and the effects due to the relative excess of the other elements. In some cases, too, there may be a large excess of some one element, and this may interfere with the solubility, absorption or utilization of another element to such an extent that acute deficiency symptoms appear, even though there is an abundant supply of the second element. Similar effects may result from the acid-alkaline reaction of the soil (or any other medium in which the plant is grown). Again, symptoms of poisoning may be added to symptoms of mineral deficiency. Finally,

there is the question of what happens when more than one element is deficient. The answer, however, is not so complex as it might be, since the visible effects are usually those characteristic of the element that is most deficient.

A deficiency of an element may occur at any time during the life of a plant, and neither its size nor its age alters the effects. As a rule the most typical symptoms are those that show up first, and these are the ones that serve best to distinguish a shortage of one element from that of another. It is not uncommon to observe more pronounced symptoms on one side of a plant or even on one-half of a leaf than on the other (11) due to failure of cross transfer of nutrients. After the diagnosis has been made, the practical remedy is usually obvious and more or less easily applied. In most cases, under field conditions it consists simply of adding the missing element in suitable form to the soil.

Even though the missing element is supplied, deficiency symptoms may occur if the element is not supplied in the right amount for the prevailing conditions, or if the conditions are such that it is unavailable for use by the plants. These are points that must be kept in mind by the grower. The tobacco plant has a relatively high content of minerals, as evidenced by the amount of ash that remains after it is burned. Its growth is rapid, and adequate supplies of the necessary elements should be constantly present in the soil.

In practice, complete absence of an essential element from the soil rarely if ever occurs. Also, the seeds contain small quantities of the essential elements, and the young seedlings are commonly grown on virgin soils liberally manured and fertilized. Thus, it is possible for the young plants to build up small reserve supplies, particularly of the elements that move readily from one part of the plant to another. Finally, commercial fertilizers—and even ordinary pure chemicals—usually contain small quantities of various elements as impurities in addition to the elements they are supposed to contain. The plant, then, is always grown under such conditions that, though a given element may be more or less deficient, it is perhaps never entirely lacking.

The most essential requirement for recognizing deficiency symptoms is a thorough knowledge of the plant itself—its life history and habits, how it looks and how it acts at all stages of growth. It is also necessary to know how diseases and insect pests affect the plant, so their effects may not be confused with the symptoms of plant-food deficiency. The successful grower has this knowledge through long acquaintance with

the plant under practical conditions. In fact, once he learns what the deficiency symptoms are, he may be able to recognize them much better than the specialized scientist, who is less familiar with the plant under all the conditions of practical culture.

Because of its large area, the tobacco leaf is an excellent subject on which to study the effects of any environmental factor on growth. Since the plant is produced for its leaf, studies of tobacco leaves during growth may eventually have an unusually important practical application. Most of the symptoms described in the following pages are found in the leaves. Other symptoms could be found, of course, by careful examination of the root or stem.

NITROGEN (N) DEFICIENCY

Under field conditions, the most common deficiency in tobacco probably is a shortage of nitrogen. As a matter of fact, the nitrogen supply for the tobacco crop must be controlled to produce leaf of a certain type. Some types of tobacco must even be grown under conditions of relative nitrogen starvation—flue-cured tobacco (17), for example, and to some extent burley and Maryland (2, 15). Cigar leaf (19), on the other hand, can be produced successfully only when there is an abundant or luxury consumption of nitrogen by the plant.

Even when tobacco must be grown under conditions of relative nitrogen deficiency, the supply cannot be reduced to the proper point until the plant has reached a certain size and stage of maturity. This is apparently an important requirement if the tobacco is to ripen properly.

The plant may show signs of nitrogen deficiency at any period of growth, from the seedling stage to maturity.

The effect first becomes apparent as a decrease in the normal green color. At the same time, growth slows down or stops.

After the first change in the greenness of the plant, the lower leaves turn lemon yellow to orange yellow, the shade apparently depending on the intensity of the green before the nitrogen deficiency occurred. The darker shades of yellow occur on the plants that had the deeper shades of green.

This yellowing is followed by a drying up, or firing, of the yellowed leaves. The number of leaves the plant loses depends on its size and the acuteness of the shortage of nitrogen.

The remaining leaves on the plant tend to assume an erect position, forming acute angles with the stalk.

The bud leaves tend to retain their normal condition. Apparently their needs are met by a transfer of nitrogen from the older leaves.

If the nitrogen shortage becomes acute at the flowering stage, flowering and fruiting are accomplished by a similar transfer of nitrogen from the older tissues, but the quantity of seed is reduced.

The effects of a deficiency of nitrogen are shown in plate 1. Here the light-green color of the plant is evident, as well as the yellowing

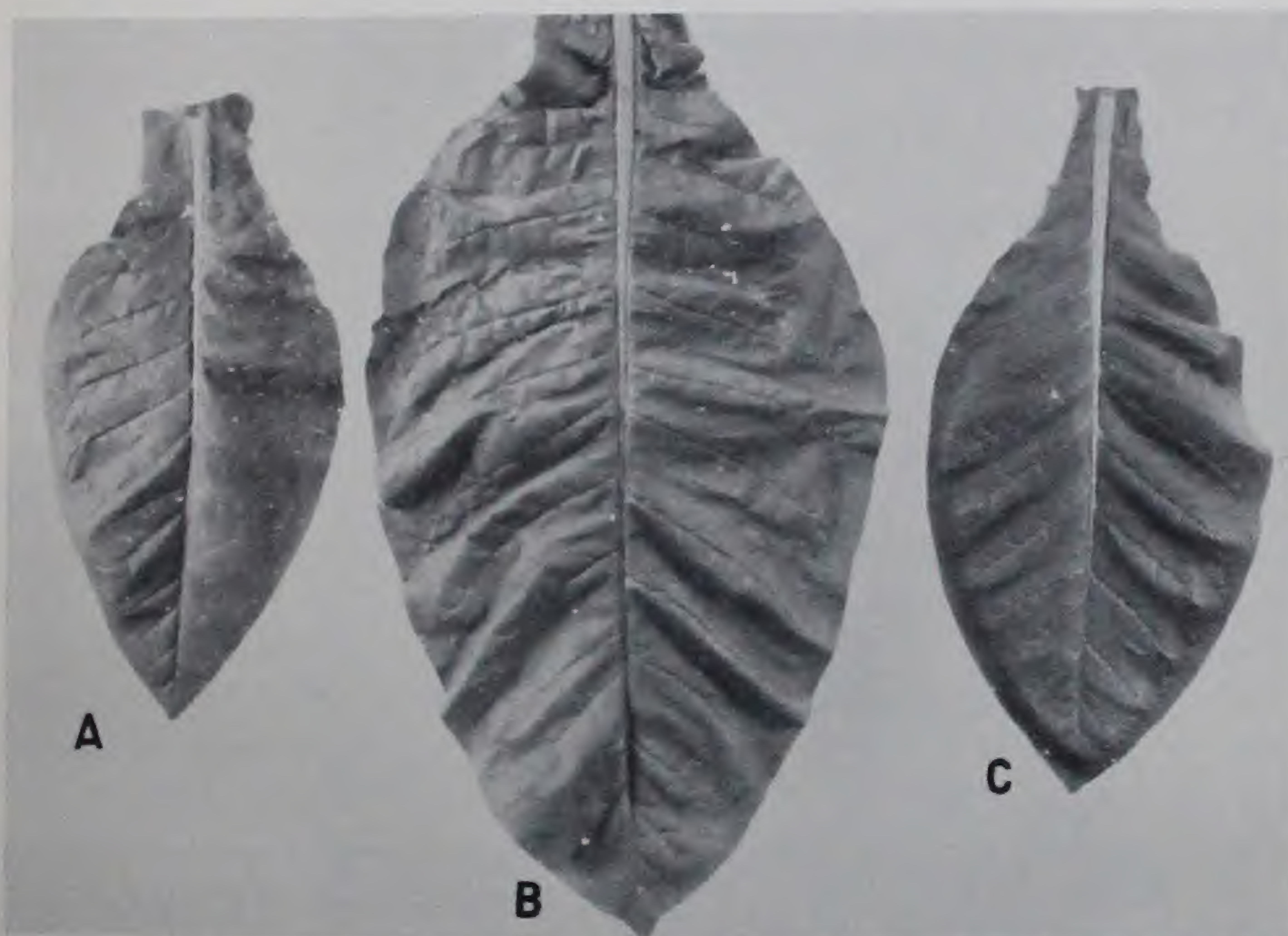

Figure 1. A and C show the small, rather narrow leaves that result from phosphorus shortage. B is from a plant liberally supplied with phosphorus.

of the lower leaves and the tendency of the unyellowed leaves to stand more upright than usual. The same symptoms have been reported in plants grown in solution cultures (9) when the supply of nutritive elements was accurately controlled.

A nitrogen deficiency appears to reduce in some way the water content of the plant. This probably accounts for the fact that a nitrogen shortage and a water shortage sometimes show much the same symptoms. A nitrogen shortage, however, may occur when the plant is standing in water all the time, as in a solution culture.

The effects of a nitrogen shortage can be seen in the cured leaf. Its

size is reduced, the amount of reduction depending on the stage at which the shortage occurred. The color is also affected, differently with different types and methods of curing. The flue-cured type of tobacco has the desired lemon-yellow color only when the nitrogen supply is reduced to the point of deficiency at the ripening stage. With the cigar type, nitrogen deficiency is decidedly injurious at any stage; it results in undesirable

Figure 2. Leaf spot such as this sometimes occurs as a result of phosphorus deficiency.

colors and other poor qualities not well understood. The nitrogen supply is also known to influence nicotine content to a great extent, low nitrogen generally producing a leaf with a low nicotine content.

PHOSPHORUS (P) DEFICIENCY

Practically all tobacco soils except those derived from phosphatic limestones are initially deficient in phosphorus. Phosphorus deficiency,

however, causes tobacco plants to exhibit growth effects less characteristic (9, 13, 19) than those resulting from shortages of any of the other essential elements.

The symptoms that serve to identify phosphorus deficiency are a certain type of slow growth and lack of maturity.

With this stunted growth, the plant assumes a rosette condition. The color is very dark green, as shown in plate 2.

The size and shape of the leaves are altered (figure 1). The leaves tend to be narrow in proportion to length. Usually, no abnormality of the leaf appears other than in size, shape, and color, but in a few instances spots have been evident on the lower leaves of the plant as shown in figure 2. These spots do not occur consistently on phosphorus-deficient plants either in the field or in solution cultures.

The leaves form acute angles with the stalk, as seen in plate 2.

Under field conditions, firing of the lower leaves does not appear to any considerable extent.

The bud leaves tend to retain their normal appearance, possibly because phosphorus is transferred to them from the older parts of the plant. Similarly, flowering and fruiting are successfully accomplished when the shortage becomes manifest at this stage of growth.

If tobacco is to have the desired quality when cured, it is essential that the leaf reach a certain stage of maturity before harvest. Leaves from plants suffering from phosphorus deficiency are immature and therefore have an undesirable quality. The cured leaf tends to be dark brown, dark greenish, or black. Maturity of the crop is frequently delayed until late in the season, when the weather is unfavorable for curing, especially in the case of the air-cured types.

POTASSIUM (K) DEFICIENCY

Tobacco requires a great deal of potassium; in fact, what would be a luxury consumption from the standpoint of yield alone seems to be necessary to produce leaf of high quality. The plants show striking symptoms when potassium is not present in adequate quantity (1, 9, 13, 19, 20) though under field conditions reduction in growth is not so marked as in the case of a shortage of nitrogen or phosphorus. Many tobacco soils do not supply sufficient amounts of potassium for normal growth, and probably the first deficiency effects reported for tobacco were those due to a deficiency of potassium. The deficiency symptoms tend to be aggravated by dry weather.

The lower leaves of the tobacco plant suffering from potassium hunger show a typical mottling, or a loss of green color (chlorosis) at their tips and margins, as shown in plate 3.

This is rapidly followed by development of specks of dead tissue (necrosis), usually as small spots in the centers of mottled areas.

Later the areas of dead tissue may enlarge and run together to such an extent that most of the leaf tissues between the veins are involved. As the dead areas enlarge and involve more and more tissue, they dry to a brown color, so that the whole plant comes to have a brownish or rusty appearance. The parts of the leaf that remain green are darker and more bluish than normal.

The dead areas may fall out, producing a ragged appearance of the leaf, as shown in plate 4.

Even before the appearance of mottling and dead spots, an affected leaf becomes cup-shaped from the underside probably because growth slows down at the edges but continues in the center. The margins seem to roll inward and downward. This crumpled effect becomes more marked as the living tissue continues to grow around the mottled and dead areas.

Figure 3. This plant, from a seedbed, shows that even seedlings may be affected by potassium hunger

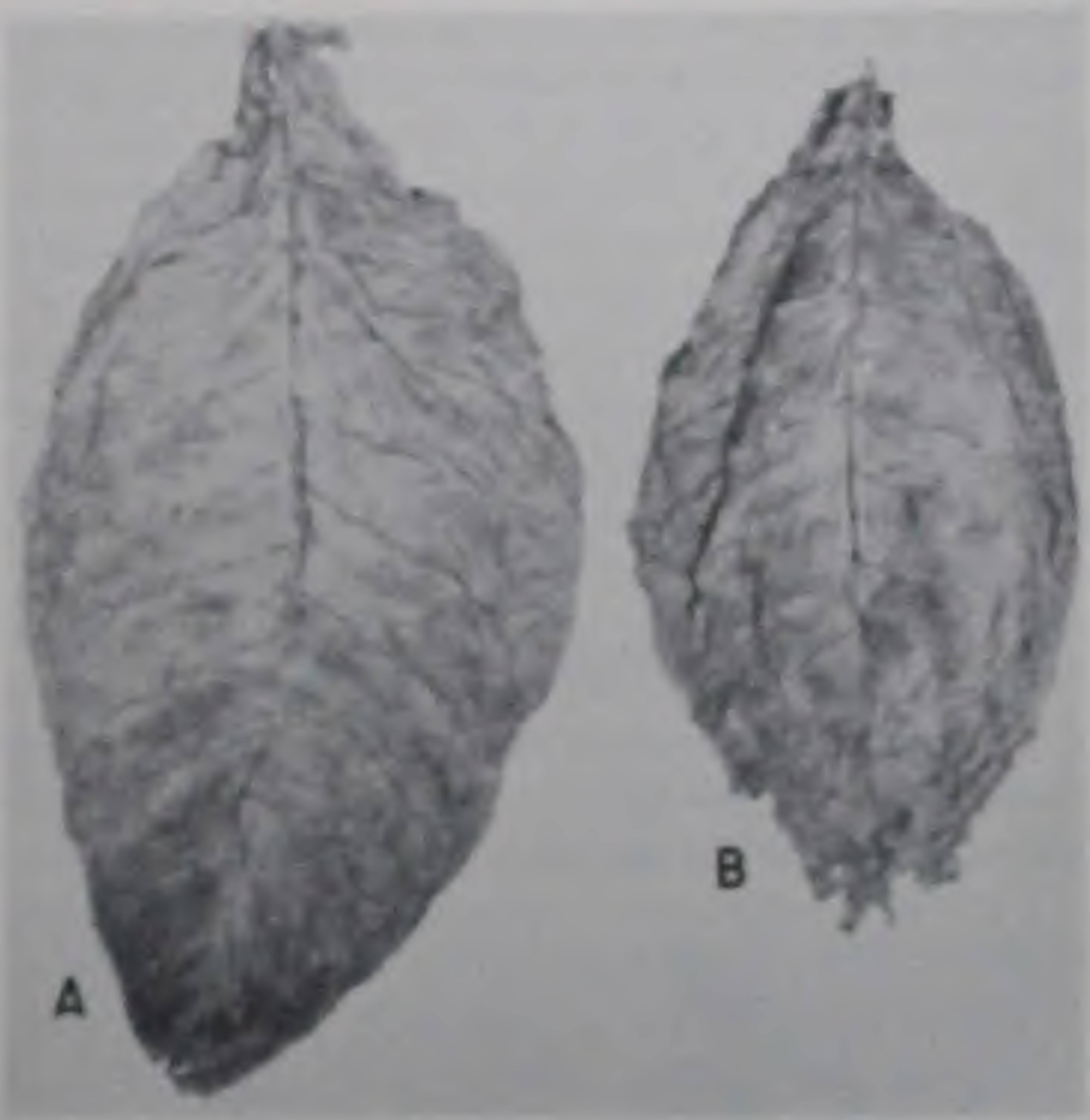

Figure 4. Cured leaf, Maryland type. A, cured leaf from a plant liberally supplied with potash. B, ragged leaf of reduced size from a plant suffering potassium hunger.

The mottling appears to progress rapidly from the lower to the upper leaves. In rapidly growing plants in the field, after the lower leaves are almost mature, the upper leaves may show mottling and spotting without the lower leaves showing any decided symptoms. There may be some loss of the older leaves, but this is not so characteristic as it is in the case of nitrogen deficiency.

In all cases observed, the bud leaves tend to retain their normal appearance, apparently because potassium is transferred to them from the older parts of the plant.

Symptoms of potassium hunger may be observed on young seedlings from the seedbed (figure 3) as well as on the large plants in the field.

It has been consistently reported that under field conditions a liberal supply of potassium enables the plant to withstand or ward off attacks of leaf spot caused by bacteria (15, 17, 19). Perhaps under conditions of shortage the development of dead areas, already described, allows the organisms causing certain leaf-spot diseases to enter the tissue at these points. This would hasten the breakdown of the tissue.

It is well recognized that in some manner potassium aids in main-

taining the general vigor of the plant. There appears to be a relationship between potassium and nitrogen in this connection. With cigar tobaccos grown under high-nitrogen conditions, the protective action of potassium found with Maryland and flue-cured types where the nitrogen supply is purposely limited, is difficult to obtain.

In the cured leaf, potassium shortage is shown by reduced size and a ragged appearance, as illustrated in figure 4B. The cured leaves are off-type in color, though they do not show the distinctive color patterns described for the growing leaves. They also lack body, elasticity, aroma, and ability to condition when exposed to moist air, and they have poor fire-holding capacity.

MAGNESIUM (Mg) DEFICIENCY

Magnesium deficiency has been given the common name of "sand drown" (3, 5, 9, 13, 17, 19) since it is most prevalent in deep sandy soils during seasons of excessive rainfall. The deficiency symptoms rarely

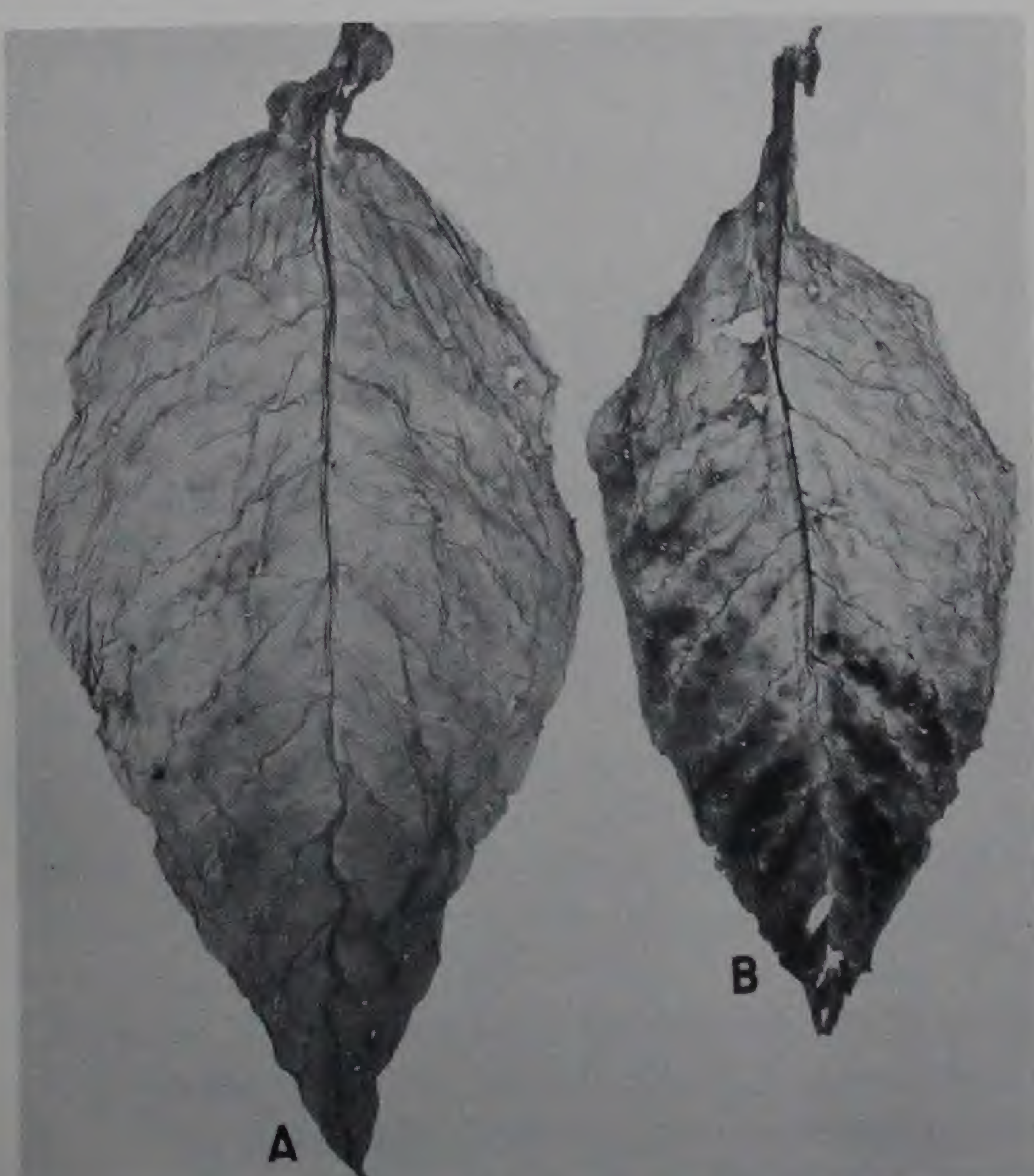

Figure 5. Flue-cured tobacco leaves. A is from a normal plant. B shows the dark, irregular patches and other signs of poor color due to magnesium deficiency.

appear in the field until the plants have attained considerable size, more commonly after topping when the growth rate is rapid. Thus the leaves usually attain almost normal size and shape. Other symptoms of magnesium deficiency, however, are very striking.

Since magnesium is part of the chlorophyll molecule, the green pigment is affected when the magnesium supply is short. The loss of green color commonly progresses in a definite manner.

First, the lowermost leaves of the plant lose their normal color at the tips and margins (plate 6) and between the veins. The color may vary from a pale green to almost white, depending on the acuteness of the shortage. The veins and the tissue close to them tend to retain the normal color long after the rest of the leaf has lost practically all its green pigment. Even in extreme cases, when the lower leaves become almost white, they rarely dry up or develop dead spots.

The loss of color, characteristic of magnesium hunger, proceeds uniformly as a rule, from the base of the plant upward (plate 5). On the individual leaf, it begins at the tip and margin and proceeds toward the base and center. The yellow as well as the green pigments appear to be affected. The entire area of the leaf and all the leaves of the plant may be involved in extreme cases, though the bud tends to remain normal.

Under experimental conditions, in solution cultures, some of the old lower leaves may not lose their green color when the plant is growing rapidly and magnesium is suddenly withdrawn. Moreover, in solution cultures the appearance of dead spots even before loss of color has been reported. This spotting also has been observed in plants grown in soil cultures in the greenhouse when the soil was leached with an excessive amount of nutrient solutions lacking magnesium. It has not been observed to any extent in field cultures, but it might possibly occur with rapidly growing plants under excessive rainfall.

The contrast between the pale and the normal tissue is sharpest in plants with a dark-green color. It is not so striking when the plant is light green because of a low supply of nitrogen or sulfur.

As has been pointed out, symptoms of magnesium deficiency usually appear when the plant has attained considerable size. They have been observed, however, even in the seedling stage, as plate 7 shows. The extent of the dwarfing that results from a magnesium shortage seems to be simply a question of when the shortage operates and how acute it is. The yield is reduced to the extent that dwarfing occurs, but as already noted this may not be severe if the shortage becomes acute only at a late stage of growth.

The reduction in the quality of the cured leaf is more serious. It is indicated by dark and irregular colors, loss in weight, dry leaf tissue, and a lack of body and elasticity. These signs of lowered quality are more evident in the flue-cured (figure 5) than in the air-cured types of leaf. Magnesium has been reported to be an important constituent in cigar tobacco and that when the magnesium content is low, the ash tends to be dark.

CALCIUM (Ca) DEFICIENCY

Calcium has long been recognized as an essential plant nutrient, but it has been erroneously assumed that all agricultural soils contain enough of it for strictly nutritive purposes. It is commonly used, in the form of hydrated lime or calcium carbonate (ground limestone), not as a food for plants but to bring about the best soil reaction for plant growth. The ions, or small electrified particles of calcium, may be said to antagonize the ions of objectionable substances, or to neutralize or render them harmless. It is quite probable, however, that in some cases favorable results are also due to the nutrient value of calcium.

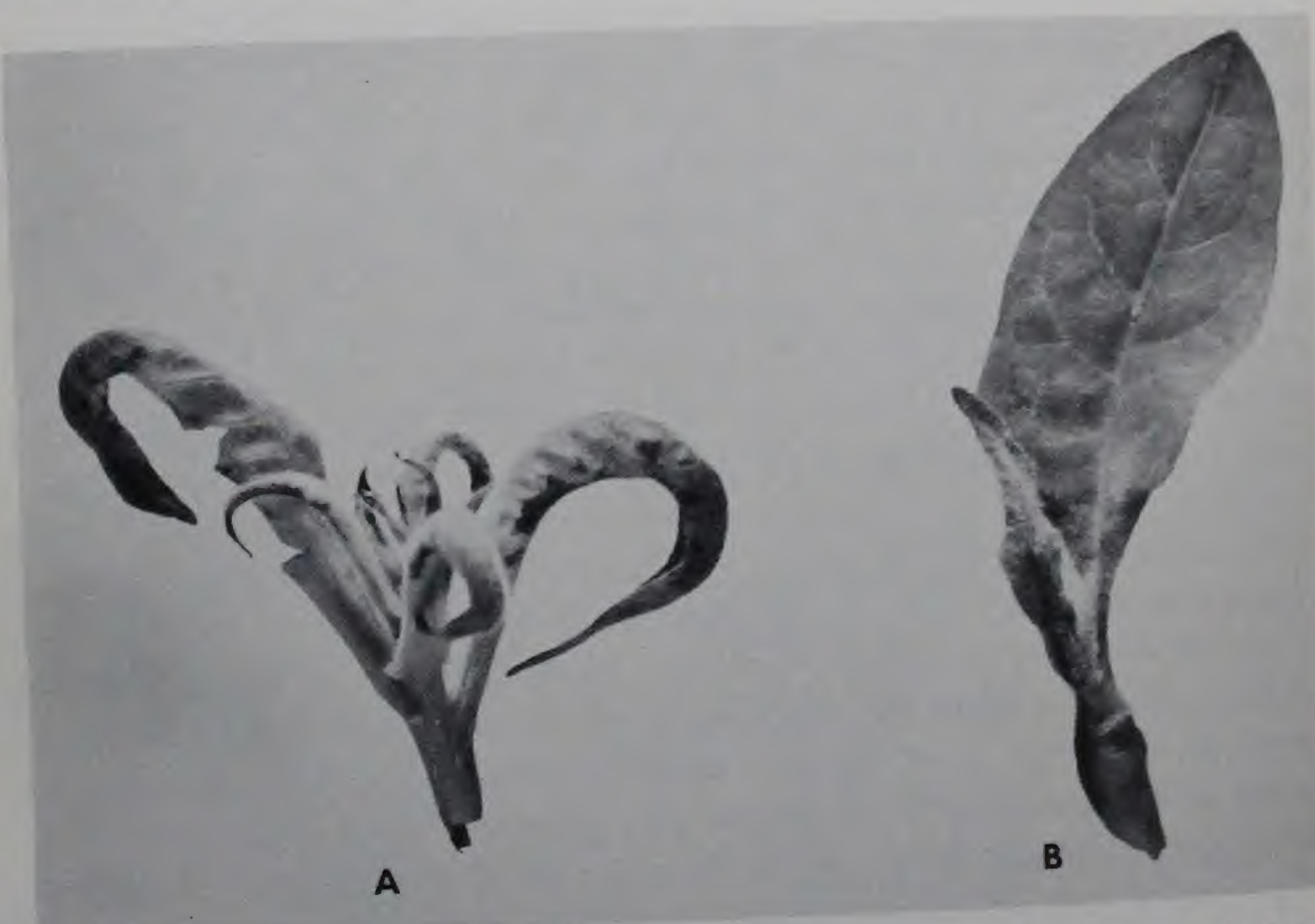

Figure 6. Terminal growth affected by mineral deficiences. A, the first stage of calcium shortage; note the hooking downward of the bud leaves; B, an early stage of boron deficiency showing breakdown of tissue at the base of the leaf.

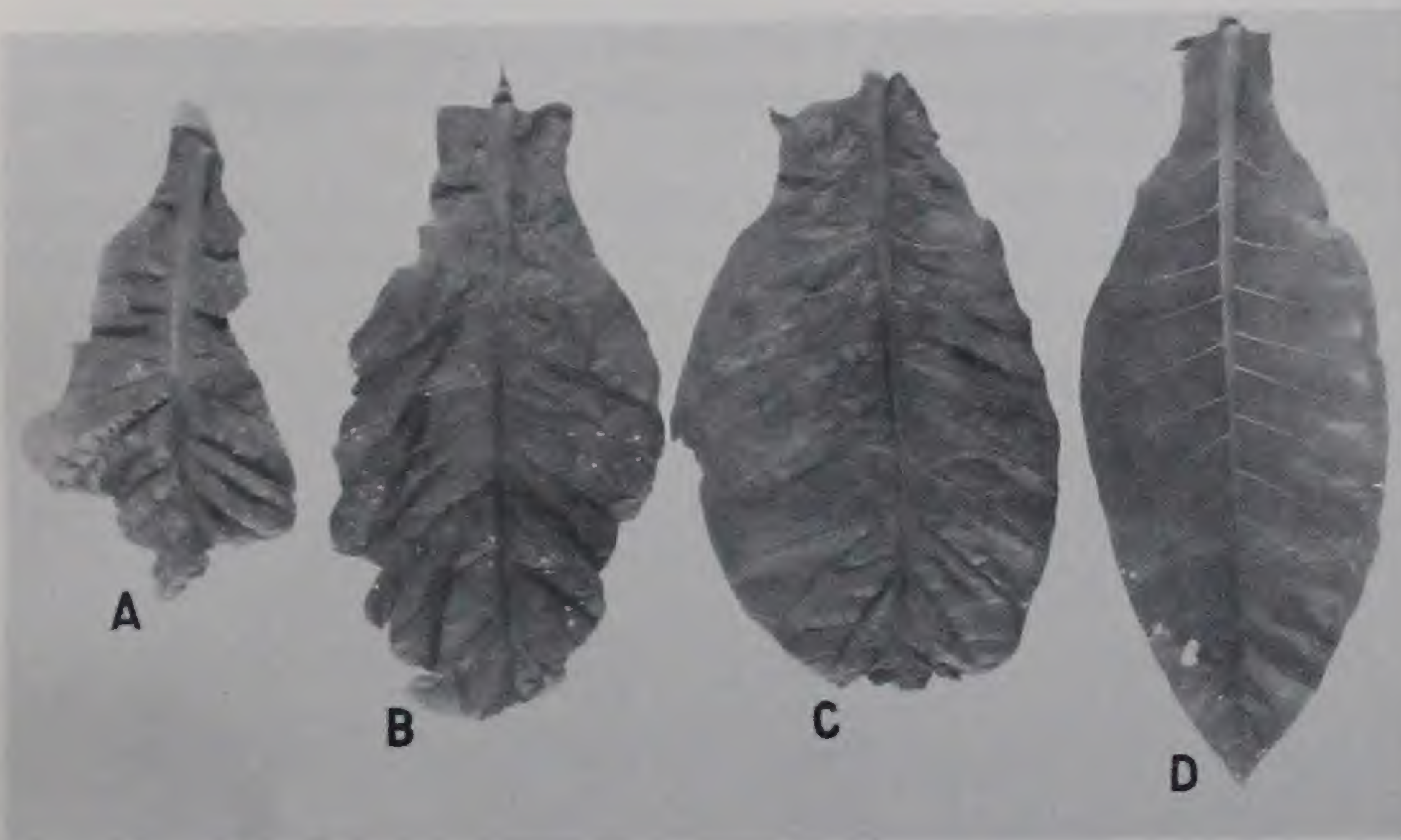

Figure 7. A, B, and C are young leaves from a tobacco plant showing the scalloped, irregular edges due to calcium deficiency. D is from a normal plant.

When the calcium supply is deficient (4, 9, 13, 19) the tobacco plant shows distinctive abnormalities in growth. Just what form these abnormalities take seems to depend to some extent on what other substances are present under a given set of conditions. This is in keeping with function of the calcium ion as an antagonizer of other ions. Magnesium gives the most striking illustration of this relationship. Quantities of magnesium that produce normal growth in the presence of calcium seem to become poisonous in its absence. What happens in this case is typical, for all practical purposes, of calcium deficiency in general.

The first symptom of calcium deficiency is the development of a light-green color, followed by a peculiar hooking downward at the tips of the young leaves making up the terminal bud (figure 6A).

This is followed typically by the death of the young leaves, which break down first at the tips and margins. If complete breakdown does not occur and growth takes place later, portions of the tips and margins of the affected leaves are missing, and this gives them a scalloped appearance (figure 7). As the illustration shows, they are also distorted. The older leaves, however, may be normal in shape (plate 9).

The calcium deficient tobacco plant as a whole is abnormally dark green. In the later stages of extreme calcium shortage, the terminal bud dies. This is equivalent to topping, and it results in a thickening of the

older leaves. In some cases of acute shortage, dead spots may develop and loss of color may occur on the older leaves, though these effects have rarely been observed.

When lateral shoots or suckers begin to develop in the leaf axils after the death of the terminal bud, their terminal growth in turn goes through the same stages, and the buds die.

Figure 8. Tobacco plant after recovery from a calcium shortage in dry weather. Note that the young leaves at the top have grown normally.

These effects were first reported on plants grown in solution cultures, and later they were found to be typical in the field.

The topmost leaves sometimes show no abnormality (figure 8) when deficiency symptoms are evident on the middle leaves. This appears to occur in dry periods, when the roots may have penetrated to greater depths than usual, enabling the plant to draw on subsoil reserves of calcium.

A symptom that has been experimentally reproduced by adding excess manganese in the presence of calcium has sometimes been observed in

the field. The young leaves lose color and then develop dead spots. In experimental work, the condition has been corrected by the application of limestone.

In the case of plants grown in the greenhouse, the floral parts show striking effects if the calcium shortage does not become acute until the flowering stage. Figure 9A shows the floral parts from a normal plant and B those from a plant grown under conditions of calcium shortage. Plant B has suffered from a tendency to shed blossoms and buds, and

Figure 9. Effects of calcium shortage on the flowering parts of tobacco. A is from a normal plant. In B note the drying up of the corolla and the distortions of the calyx.

the flowers that remain show a dieback of their corollas with their pistils protruding. In most cases there are spots of dead tissue on the calyx lobes. This condition has been observed commonly in the field.

It is evident from these various symptoms that little or no calcium is transferred from the older tissues to the growing points, as in the case of the elements previously described. This means that if normal growth is to occur there must be a continuous supply of calcium available to the plant.

The effects of calcium deficiency on growth are disastrous to the cured leaf. The malformation and thickening of the leaf, the death of the terminal bud, and the other physiological disturbances combine to produce a tobacco of extremely poor quality.

BORON (B) DEFICIENCY

The effects of boron starvation on plant growth had been reported in experiments with solution cultures (8, 9) some time before they were recognized under field conditions (7, 10, 19).

An acute boron shortage first produces marked changes in the tip or growing point of the plant.

The young leaves of the terminal bud become light green in color—paler at the base than at the tip. They also show a somewhat drawn appearance. When these symptoms appear, the leaves have already ceased to grow.

Next, the tissues at the base of the young leaves show signs of breakdown (figure 6B). If growth should take place later, before all the tissues are broken down, these leaves would be distorted by the growth around the injured tissue. Usually they have a one-sided or twisted appearance. The stalk toward the top of the plant may also show a distorted or twisted type of growth.

Death of the terminal bud (plate 10) follows these stages. This automatically tops the plant, causing the leaves to thicken and increase in area. The upper leaves tend to roll in half-circles downward from their tips toward their bases. They are abnormally light in color and become smooth, stiff, and brittle. When the midrib or secondary veins are broken, the vascular tissues show a dark discoloration.

Lateral buds (suckers) may develop in the axils of leaves or at the bases of the stalks, but they typically break down like the terminal bud.

When boron shortage does not become acute until the flowering stage, the flower buds are shed and no seed pods are set.

These symptoms indicate that little or no transfer occurs of boron from the older plant parts to the younger growing points. Therefore, a continuous supply must be available for normal growth. Only a very minute amount or trace of boron, however, is needed or even tolerated by the plant. Any considerable amount acts as a poison.

It has not been possible to make extensive observations of the effects of boron deficiency on the cured leaf. From the observations available, it is evident that marked effects are to be expected in view of the striking modifications in growth produced by boron shortage.

MANGANESE (Mn) DEFICIENCY

When tobacco plants apparently manifesting a new disease were submitted to the Department of Agriculture by a grower, identification of

the symptoms as those of manganese hunger was possible because the same symptoms had been produced experimentally in sand and solution cultures. Later the identification was substantiated by field trial on the area from which the plants were taken.

Distinctive symptoms of manganese shortage, however, have been reported in only a few cases in the field. Perhaps they are rare because this deficiency is usually associated with a neutral or alkaline soil reaction. Such a soil reaction favors the black root-rot disease (*Thielaviopsis basicola* (Berk. and Br.) Ferraris), which limits growth and tends to hide the effects of a shortage of manganese.

The first visible symptom of manganese hunger (9, 13, 16, 19) is a loss of color in the young leaves. This loss of color follows out the minutest branches of the veins, or vascular system. Between the veins the tissue is light green to almost white (plate 8-3), while the veins themselves remain darker. The leaf has a checkered appearance because of the contrast between the green veins and the tissues that have lost their color.

Loss of color is followed by development of spots of dead tissue, which may drop out, giving the leaf a ragged appearance. Usually this spotting is not confined to tips and margins, as in the case of potassium deficiency, but involves parts scattered over the entire leaf.

The plant as a whole may be considerably dwarfed (plate 11-2), and in general appearance it is light green.

The cured leaves from plants affected by manganese shortage are of decidedly poor quality. The most apparent effects are the dead spots and the lack of desirable color (plate 12). The leaf also lacks body, elasticity, and aroma.

SULFUR (S) DEFICIENCY

Tobacco plants suffering from sulfur deficiency have not often been found under field conditions (13) chiefly, perhaps, because most commercial fertilizers contain ample amounts of sulfur, many of their common ingredients being high in this element. In addition, rainfall in the tobacco-growing regions usually brings down considerable quantities of sulfur from the air. In fact, sulfur deficiency becomes evident in dry periods, when the shortage is produced intentionally.

The first evident symptom is the light-green color of the plant as a whole, though there is a tendency for the young leaves to be lighter than the older ones. In solution cultures (9) the light-green color is largely confined to the younger leaves.

The plants do not lose their lower leaves by firing, as they do in the case of nitrogen shortage. This fact serves to distinguish the two deficiencies.

In Georgia and South Carolina, some blistering of the flue-cured tobacco has been associated with sulfur deficiency.

There may be some reduction in growth and frequently there is a characteristic crimping downward of the leaves at the tips (plate 13B).

As a rule, the effects of sulfur deficiency have been apparent under field conditions only in the early stages of growth. They are evident only during dry periods, and recovery has been observed to take place rapidly and completely when rain occurred. Apparently the rain supplies the needed sulfur.

The cured leaf of plants suffering from sulfur shortage shows color effects that are sometimes desirable and sometimes undesirable. In the case of flue-cured leaf, a sulfur deficiency may be advantageous, provided yields are not seriously reduced; it produces more desirable colors than an overabundance of sulfur. In Maryland leaf, on the other hand, an abundant sulfur supply produces the more desirable colors.

IRON (Fe) DEFICIENCY

As yet, iron deficiency has not been observed in tobacco under field conditions. It has been reported as occurring in plants (6) other than tobacco (9, 13, 16) grown in sand or solution cultures. In the case of plants other than tobacco, iron deficiency is associated with neutral or alkaline soils. This might account for the failure to find it in field-grown tobacco, since the situation would be complicated by the root-rot organism mentioned in the case of manganese deficiency.

A leaf of a tobacco plant grown experimentally under conditions of iron shortage is shown in plate 8-1. The leaf is suffering from chlorosis or loss of green color typical of other plants affected by iron deficiency; in fact, for a long time this was the only recognized type of chlorosis occurring in plants.

As shown in plate 14, the loss of color first becomes evident in the young or upper leaves (9, 13, 16) of the tobacco plant. The leaves making up the terminal bud lose color between their veins and become light green or white. In extreme cases the veins also lose their color and the whole terminal bud may turn almost white. Usually, however, the principal veins tend to retain their color, as do the lower leaves.

The affected leaves characteristically show no breaks or areas of

dead tissue, though sometimes they dry up. Apparently this occurs under conditions of bright sunlight and dry air.

The fact that the growing point is immediately affected indicates that iron is not transferred from the older parts of the plant and that a continuous supply must be available if growth is to be normal.

COPPER (Cu) DEFICIENCY

As in the case of iron, symptoms of copper shortage have not yet been observed in tobacco under field conditions, though they have been observed in other plants. Since they have been associated with soils high in organic matter, like those on which tobacco is sometimes grown, it

Figure 10. Effect of copper deficiency on growth of tobacco. A, normal plant grown in nutrient solution with copper added; B, plant grown without copper; note the extreme and permanent wilting of the upper leaves.

seems worth while to describe the effects of copper hunger on tobacco plants (16) grown experimentally in the greenhouse.

As shown in figure 10B, the upper leaves are unable to retain their turgor or rigidity, so that they wilt badly. Such plants are permanently wilted; they do not recover at night or during cloudy periods like plants that have wilted on a hot day.

There is a reduction in growth in proportion to the extent of the copper shortage and the stage of growth at which it operates.

When a copper deficiency becomes evident during the flowering stage,

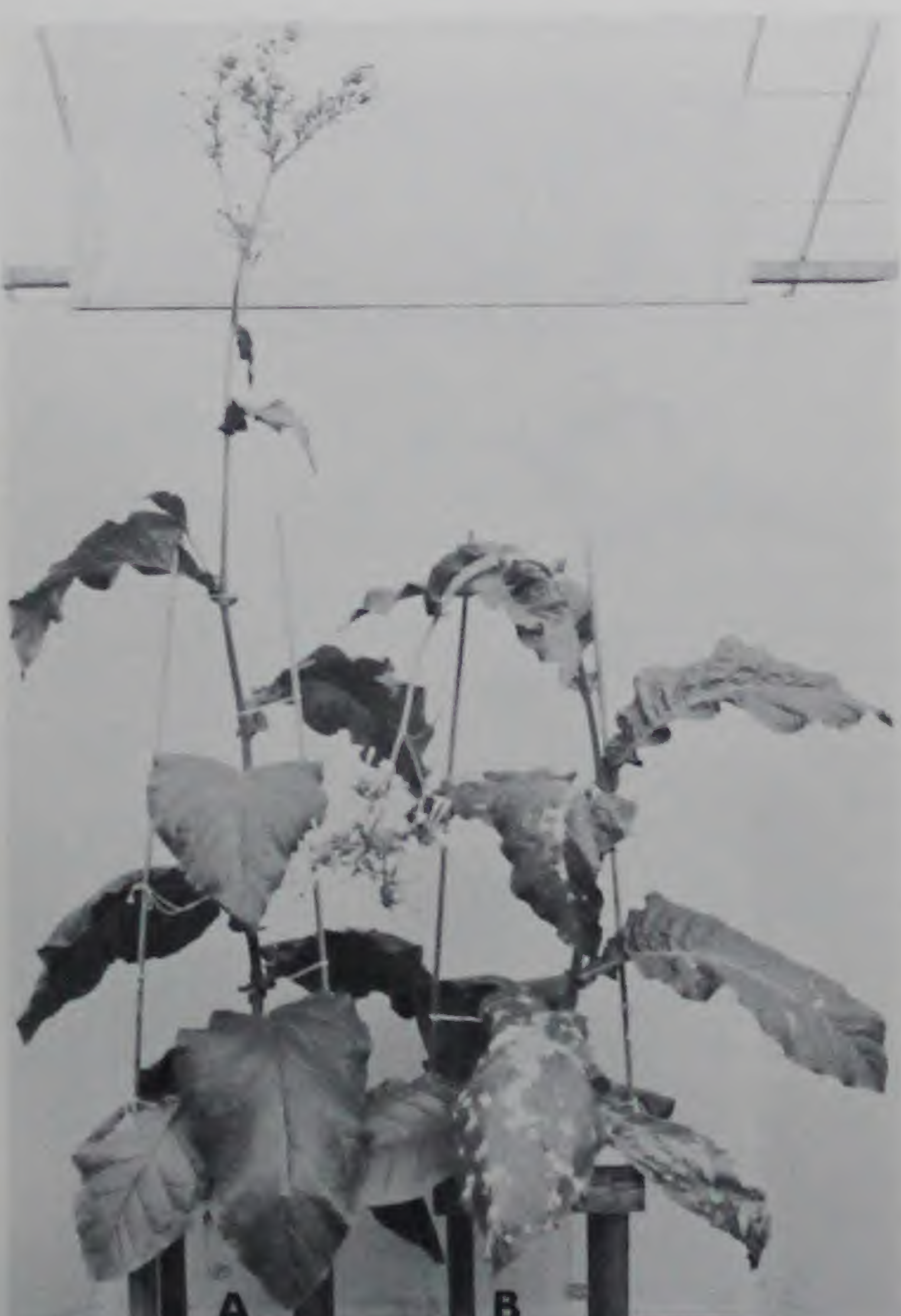

Figure 11. Effects of copper deficiency on growth of tobacco plants in solution cultures. Note bending of stalk immediately below seed head and leaf spots on lower leaves. A, copper applied; B, copper withheld.

the seed stalk does not stand erect (figure 11 and plate 16), and the amount of seed is reduced.

Copper is one of the elements needed by plants only in very small amounts. In nutrient solutions, the amount needed to correct a deficiency was found to be from one-sixteenth to one-eighth part per million—equivalent to half an ounce of copper in some 30 to 60 thousand gallons of water. Amounts in excess of these small quantities produced a decided stunting of the plants.

Under field conditions, the amount to be applied would depend on the fixing power of the soil for this element. The chemical situation would seem to make it inadvisable to include copper compounds in standard fertilizer mixtures at least until there is evidence that copper is deficient in a wide variety of soils, since the phosphates would combine with copper to form cupric phosphate, which is relatively unavailable for use by plants because it does not easily dissolve. In case of deficiency, it may prove best to apply the copper as a spray directly on the plants.

ZINC (Zn) DEFICIENCY

Zinc is another element not known to cause deficiency symptoms in field-grown tobacco. However, there is a disease of tobacco, occurring in wet periods, characterized by a leaf spot commonly attributed to bacteria. It causes a breakdown of the leaf (15, 17), and frequently a large part of the crop is severely damaged. The symptoms correspond in many respects to those produced experimentally by a shortage of zinc. It is not possible to say with certainty as yet whether zinc deficiency is a factor in this disease.

Striking effects are produced in the plant (16), as shown in plate 15B, when zinc is withheld in sand or solution cultures.

Typically, the lower leaves first show a slight loss of color at their tips and margins. This is followed by development of areas of dead and broken-down tissue. Usually a small area is involved at first, and in some cases this area is surrounded by a halo such as has been reported for leaf spots produced by bacterial inoculation.

In most cases the dead areas, which at first have a water-soaked appearance, spread rapidly. Frequently an almost total collapse or death of the leaf tissue follows in a very short time. The breakdown may come so quickly that the early stage, characterized by loss of color, may not be evident. Sometimes, too, the lowermost leaves of the plant are not the only ones involved.

The small veins are not involved at first, but frequently they also soon break down.

As a rule, the dead leaf tissue finally dries to a brown color.

There is some shortening of the internodes—the spaces between the leaves on the stem—and the green leaves appear to be thickened and greener.

In some ways these symptoms resemble those described for potassium hunger. There are distinct differences, however. In the case of potassium shortage, the first breaks or lesions in the tissue are more sharply confined to the leaf tips and margins; the small veins do not ordinarily break down at all; and the breakdown proceeds much more slowly.

As in the case of copper, it does not appear advisable at present to include zinc in fertilizer mixtures. Zinc would combine with soluble phosphates to form zinc phosphate, which cannot readily be dissolved, particularly in alkaline soils. The use of small amounts of zinc is sometimes desirable, but spraying seems to be the most practical method of application. In any considerable amount, zinc is poisonous to most plants.

MOLYBDENUM (Mo) DEFICIENCY

The importance of traces of molybdenum for the growth of tobacco has been pointed out (14). This was described in more detail by Steinberg (18) in 1953. Molybdenum deficiency causes more or less characteristic chlorosis of the lower leaves followed by crinkling, bending, and twisting (figure 12) of the leaves with a later development of necrotic areas, as shown in plate 17, which may eventually enlarge. Production of seed is reduced due to shedding of the flowers.

The amount of molybdenum required to prevent deficiency so extreme as to prevent flowering in tobacco has been estimated by Steinberg (18) as a decrease of 0.02 to .2 parts per billion or .2 to 2.0 micrograms per plant. The occurrence of molybdenum deficiency has been found to be more common on unlimed soils. It also appears to be more prevalent with high nitrate content of the leaves.

The addition of molybdenum to tobacco fertilizers has not been shown to be necessary since no case of a known deficiency of this element has been reported as occurring in tobacco under field conditions.

RECOGNIZING COMPOUND DEFICIENCIES

In practical plant culture, where the causes of an abnormal condition cannot be determined from the nature of the treatment given the soil

Figure 12. Effects of molybdenum deficiency on growth of tobacco plants in solution cultures. A, molybdenum added; B, molybdenum withheld.

as they can be in experimental work, it is necessary to make an accurate diagnosis from the symptoms alone. For this reason, various combinations of mineral deficiencies were tried out under field conditions to see what the symptoms would be under these circumstances. Not all of the possible combinations have been tested, but so far, with a single exception, there has been little or no blending of symptoms; the visible effects have always been those of one deficiency which appeared to dominate the rest.

This should simplify the problem of diagnosis and treatment. If there

should be more than one deficiency, the dominant one can be recognized and corrected, then the next that appears, and so on.

When potassium, calcium, and magnesium were withheld, the symptoms were essentially those of potassium deficiency, though the reduction in growth was more extreme. When the potassium shortage was corrected, the plants still showed a marked reduction in growth, but the other symptoms were those of magnesium shortage alone, without any signs of calcium deficiency.

On untreated plots without any added fertilizer, the plants usually show the symptoms of nitrogen deficiency. In some cases, however, the dominant symptoms have been those of potassium deficiency alone, or phosphorus deficiency alone, or even sulfur deficiency alone.

The one case of blended symptoms so far observed occurred with a combined shortage of magnesium and sulfur, experimentally produced. Here, the sulfur shortage gave the plants a light-green color and, as already pointed out, this tended to mask the striking color pattern ordinarily produced by magnesium hunger.

COMPARISON OF SYMPTOMS

So far, the symptoms produced by these mineral deficiencies have been described one by one. As already said, the symptom common to all of them, though it may be more marked in some cases than in others, is reduced growth. This is clearly shown in figure 13, in which a normal tobacco plant is placed beside six abnormal plants, each affected by a different deficiency.

The symptoms other than reduced growth will now be compared to bring out the differences between them.

The first thing that strikes the observer making such a comparison is that the symptoms of mineral shortage can be classified into two broad groups.

In one broad group, primarily the older leaves are affected. This occurs with deficiencies of nitrogen, phosphorus, potassium, zinc, and magnesium. Apparently, when there is a deficiency of one of these elements in the soil, the element can be readily transferred from the older parts of the plant to the young growing parts, so that the new growth does not show deficiency signs.

In another group, primarily the new growth and young leaves are affected. This occurs with deficiencies of calcium, boron, sulfur, iron, copper, and manganese. The elements apparently cannot be moved readily from one part of the plant to another. The needs of the growing

Figure 13. A healthy tobacco plant in comparison with others suffering from various mineral deficiencies: B, nitrogen; C, phosphorus; D, potassium; E, boron; F, calcium; G, magnesium. Reduction of growth has occurred in all except A.

parts are, therefore, not supplied when there is a deficiency in the soil, and these parts sicken and die.

The first thing to look for in diagnosing a deficiency, then, is the part of the plant that is affected. This will tell in which major group the deficiency belongs.

In the first broad group, those having symptoms primarily in the older parts of the plant, the effects can be subdivided into 1) those that are more or less general, and 2) those that are local.

General effects on the plant as a whole or on the older leaves are produced by nitrogen and phosphorus deficiencies. These two, then, make up subdivision 1. In both cases there is considerable dwarfing, and the leaves tend to assume an erect position, forming rather acute angles with the stalk. In the case of nitrogen deficiency, the plant is abnormally light green, and more or less firing is evident on the lower leaves. In the case of phosphorus deficiency, the plant is abnormally dark green, little or no firing is evident, and the leaves are unusually narrow in proportion to their length.

Local effects on the older leaves are produced by magnesium, zinc, molybdenum, and potassium deficiencies. These four make up subdivi-

sion 2. The local effects are loss of green color (chlorosis) and sometimes the development of areas of dead tissue (necrosis).

In the case of potassium deficiency, the chlorotic areas are yellowish and produce a mottled effect. They surround small dead spots or specks at the tips and margins of the leaves and between the veins. As the dead areas develop and dry up, they give the leaves a rusty appearance. Other parts of the plant are bluish green. An early symptom of potassium deficiency is a crimping under or cupping downward of the lower leaves at the tips and margins, and this becomes more pronounced as the deficiency becomes more acute.

In the case of magnesium deficiency, the pale areas are light green to almost white and occur between the principal veins, not primarily at the tips and margins. There is little or no spotting with dead tissue or cupping under of the tips and margins of leaves.

In the case of zinc deficiency, dead spots develop all over the leaf, not specifically at the tips and margins. Frequently they involve secondary and sometimes primary veins. The dead areas break down much more rapidly than in potassium deficiency.

While with molybdenum deficiency the leaves are light green due to small chlorotic areas over the entire leaf area, this chlorosis is followed by development of leaf breakdown producing spots of dead leaf tissue.

In the second broad group those deficiencies characterized by effects on the young leaves or terminal growth can be classified into two subdivisions: 1) chlorosis, or loss of color in the young leaves without death of the terminal bud, which indicates a deficiency of copper, iron, sulfur or manganese; and 2) death of the terminal bud preceded by loss of green color in the bud leaves, which indicates a deficiency of calcium or boron.

In subdivision 1, identified by chlorosis of the young leaves without dieback of the terminal bud, the veins tend to retain their green color if iron is the deficient element. This loss of color usually takes place only between the principal veins, although they too may be affected in extreme cases, when the entire leaf becomes white or yellow. Usually, there are no dead spots.

If copper is the lacking nutrient, the dominant symptom is permanent wilting of the upper leaves. Lower leaves may show spots due to breakdown of leaf tissue. Stalks bend immediately below the seed head and are unable to stand erect when shortage is acute at the flowering stage.

If sulfur is the deficient element, the veins as well as the rest of the

leaf tend to be light green; in fact, they may be even lighter than the rest of the leaf. Not as great a loss of color occurs as in the case of iron or manganese deficiencies, so that the leaves do not become white or yellow. There are no dead spots.

If manganese is the deficient element, the entire vein system of the leaf even to the minutest branches retains its green color in sharp contrast to the pale tissue between the veins. This gives the leaf a checkered appearance. Later, these leaves develop small dead spots scattered over the surface.

In subdivision 2, identified by death of the terminal bud, if calcium is the deficient element the young bud leaves first lose their green color and hook downward for about one-third of their length. Then the tips and margins of these leaves die, so that if growth occurs later they look scalloped and distorted. The plant is dark green.

If boron is the deficient element, the young bud leaves first lose color at their bases and develop a drawn appearance. Their tips may remain green for some time. Usually the affected tissue breaks down rapidly, and if growth occurs later, the leaves have a distorted or twisted appearance. The color of the upper leaves of the plant is an unhealthy light green, and they roll downward in semicircles from their tips toward their bases. The principal veins and the midribs of affected leaves are extremely brittle, breaking readily when folded, and the tissue of the veins is discolored brown or black.

The key that follows has been worked out for quick identification of unknown plant-food deficiencies in tobacco.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF TOBACCO

A. Causal parasites or viruses present (not included in present discussions). Parasitic and virus diseases.

A. Causal parasites or viruses absent. More or less localized effects and decreased growth. Commonly classed with nonparasitic diseases.

Element Deficient

- B. Effects localized on older or lower leaves or more or less general on whole plant.
  - C. Local, occurring as mottling or chlorosis with or without spots of dead tissue on lower leaves; little or no drying up of lower leaves.
    - D. Lower leaves chlorotic and typically show no dead spots. Tips and margins turned or cupped upward. Stalks slender. . . . . Magnesium
    - D. Lower leaves mottled or chlorotic with small or large spots of dead tissue.
      - E. Small spots of dead tissue between the veins at leaf tips and margins which are tucked or cupped under. Stalks slender. . . . . Potassium
      - E. Spots rapidly enlarge involving the tips and margins of leaf or distributed over leaf. Leaves dark or light green.
        - F. Leaves dark green. Spots rapidly enlarge at tips and margin involving the primary and secondary veins. Leaves thick. Stalks with short internodes . . . . Zinc
        - F. Leaves light green due to chlorosis over entire leaf followed by spotting . . . . Molybdenum
  - C. Effects general on whole plant; also yellowing and drying up or "firing" of lower leaves. Plant light or dark green.
    - D. Plant light green. Lower leaves yellow, drying to a light-brown color. Stalk short and slender if element is limiting in later growth stages . . . . Nitrogen
    - D. Plant dark green. Lower leaves may yellow and dry to a greenish-brown to black color; stalk short and slender if element is limiting in later growth stages. . . . . Phosphorus
- B. Effects localized on newer or bud leaves of plant.
  - C. Terminal bud dies. Death is preceded by peculiar distortions at the tips or bases of young leaves making up the bud.
    - D. Young leaves making up terminal bud first typically hooked, then die back at tips and margins so that later growth of such leaves produces a cut-out appearance at tips and margins. Stalk finally dies back at terminal bud . . . . Calcium
    - D. Young leaves making up terminal bud first light green at base; then breakdown may take place at base of young leaf; if later growth follows, leaf shows twisted growth. Stalk finally dies back at terminal bud . . . . Boron
  - C. Terminal bud remains alive; wilting or chlorosis of newer or bud leaves, with or without spots of dead tissue; veins light or dark green.
    - D. Young leaves permanently wilted, no marked chlorosis, spotting may occur on older leaves. Stalks immediately below seed head unable to stand erect when shortage is acute at flowering stage . . . . Copper

Element Deficient

D. Young leaves not wilted, chlorotic with or without spots of dead tissue scattered over leaf.

E. Young leaves chlorotic with spots of dead tissue scattered over leaf. Smallest veins tend to remain green, producing a checkered effect on leaf. . . . . .Manganese

E. Young leaves chlorotic without dead spots. Chlorosis does or does not involve veins so as to make them dark or light green in color.

F. Young leaves with veins of a light-green color or of same shade as tissue between veins. . . . . .Sulfur

F. Young leaves chlorotic, principal veins typically green. Stalk short and slender. . . . . .Iron

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Plate 1. A tobacco plant grown under conditions of nitrogen shortage. Note the light-green color and the firing of the lower leaves.

Plate 2. Symptoms of phosphorus deficiency in tobacco. Note the abnormally dark-green color and erect position of the leaves.

Plate 3. A tobacco plant suffering from potassium hunger. Note the loss of color at tips and margins of leaves and the spots of dead tissue associated with cupping under of leaves.

Plate 4. Potassium hunger in tobacco. Left, leaf from base of plant already has a ragged appearance. Center, leaf from higher up is less affected. Right, leaf from still nearer the top has just begun to be affected.

Plate 5. Magnesium deficiency in tobacco. Four leaves, from the base of the plant upward (left to right), showing stages in loss of color. The lower leaves are the first to be affected.

Plate 6. Magnesium deficiency (sand drown) in tobacco. Note the loss of color in the lower leaves, especially at tips and margins.

Plate 7. Tobacco seedlings from plant bed. Left, normal, 2 weeks after the soil was treated with 4 pounds of Epsom salts per 100 square yards. Right, from untreated portion of seedbed, shows magnesium deficiency symptoms. Compare color and root development of the plants.

Plate 8. Tobacco leaves suffering from two mineral deficiencies: 1, Iron—note the loss of color except along the principal veins; 3, manganese—note the checkered appearance and associated dead spots. 2 is a leaf from a normal plant.

Plate 9. Tobacco plant suffering from calcium shortage. The young leaves are distorted, while the older, lower leaves look normal.

Plate 10. Boron shortage in tobacco. Note distorted upper leaves and dead terminal bud.

Plate 11. 1, is a normal tobacco plant. 2 shows dwarfing, light-green color, and dead tissues due to manganese deficiency.

Plate 12. Hands of cured tobacco, Maryland type. 1, from normal plants; 2, from plants suffering from manganese shortage—note the lack of desirable color and the spots.

Plate 13. A is a normal tobacco plant. B shows the reduced growth and crimping downward of leaves at tips characteristic of sulfur shortage.

Plate 14. Iron chlorosis in tobacco. A is a normal plant. B was grown in a sand culture to which no iron was added; note loss of color in the upper leaves.

Plate 15. Tobacco plants grown in sand culture, with zinc A, and without zinc B. Note the loss of color and the spotting of leaf tissues in B.

Plate 16. Tobacco plant grown in solution culture to which no copper was added. Note bending of stalk immediately below seed head and shedding of flowers.

Plate 17. Tobacco plant grown in solution culture to which no molybdenum was added. Note chlorosis and spotting of lower leaves.

Chapter V

Nutrient Deficiencies in Legumes for Grain and Forage

By Werner L. Nelson and S. A. Barber*

DEFICIENCY of an element does not directly produce a given symptom in a given crop or type of plant. Rather it throws normal growth processes out of balance, with the result that certain unused intermediate organic compounds accumulate, and others become in short supply. This leads ultimately to the abnormal conditions recognized as symptoms having definite relationships to the nutritional environment of growing plants. For example, the compound diamine putrescine forms in the presence of potassium deficiency in some plants and causes characteristic symptoms.

Hidden hunger refers to the situation where a crop needs more of a given nutrient or nutrients, yet does not show marked symptoms of shortage as we usually think of them (figure 1). Historically, agriculture in United States was developed on a basis of mining the soil (figure 2). However, as agriculture changes from an art to a business, fewer crops are being grown at a deficiency level. Hence, it would be a mistake to emphasize obvious deficiencies without pointing out hidden hunger. By the time noticeable symptoms appear in a crop, the grower has lost greatly in profits. With most crops, significant responses to nutrient applications can be obtained without the appearance of marked visible symptoms of need.

"SURE" LEVEL OF NUTRITION

A progressive concept of plant nutrition is one of insurance against seasonal variations in need (figure 1). We buy fire insurance on our homes hoping never to collect. Similarly, consideration of the insurance features in plant nutrient applications is worthwhile. Fertilizing to the

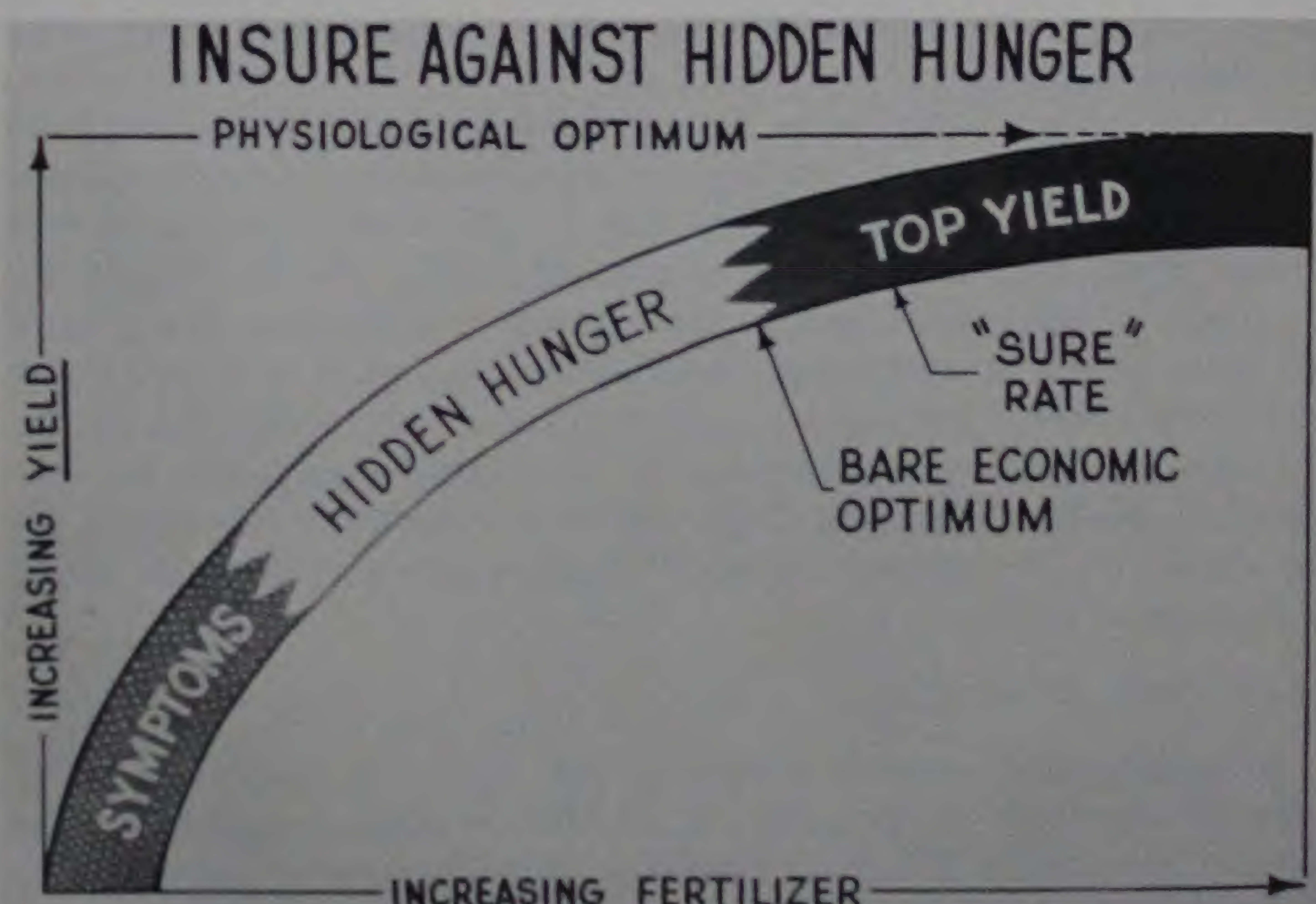
*Midwest Director, American Potash Institute, and Professor of Agronomy, Purdue University, respectively. This chapter in the first edition was written by E. E. DeTurk, University of Illinois, and in the second edition by Werner L. Nelson and F. E. Bear, Editor of "Soil Science."

"sure" level results in some nutrients remaining in the soil for a succeeding crop. Hence, the practice becomes attractive economically.

Production of forage legumes in conjunction with grasses is of interest. Often the legume simply disappears without notice of obvious symptoms by the grower. The important point is to prevent hidden hunger (and deficiency symptoms) rather than to correct it. Soil testing is an important tool (figure 3). Quick plant tissue tests help us plan better fertilizer programs for next year (figure 4). Review Chapter II for further explanation of tissue testing. Chemical analyses of plant parts also provide clues to hunger signs.

Plant families have certain distinguishing characteristics in make-up and in physiology. Legumes have pods in which the seeds are borne. A more important distinguishing characteristic is the presence of nodules on the roots. Symbiotic bacteria in these nodules "fix" gaseous nitrogen into organic compounds which then are incorporated into various substances in the plants.

Many of the legumes indicate certain nutrient unbalances with characteristic deficiency symptoms. Much work has been done to identify



Courtesy of American Potash Institute

Figure 1. Hidden hunger creeps up on crop growers unawares. Insurance against hidden hunger is obtained by use of diagnostic procedures and application of nutrients at "sure" rates.

Figure 2. Crop production based on use of plant nutrients already in the soil is historic practice. Obviously soils will vary greatly in how long they can be cropped without yield reduction before a particular nutrient must be added. Diagnostic techniques including soil and plant tests and deficiency symptoms are helpful in determining when additions are needed. The soil on the left has been mined for many years.

the causes of chlorotic conditions and plant malformations that appear. Crop variety, balance of nutrients, soil structure, rainfall, light, and temperature all affect the appearance of symptoms. Readers desiring deeper technical understanding of factors affecting hunger signs in legumes are referred to the list of "Selected References" that appears at the close of this chapter.

DEGREES OF NUTRIENT HUNGER

The degrees of nutrient hunger in legumes as well as many other plants might be classified as follows:

1. Complete crop failure at seedling stage.
2. Severe stunting of plants.
3. Specific leaf symptoms appearing at varying times during the growing season.
4. Internal abnormalities, such as clogged conductive tissues.
5. Delayed or abnormal maturity.

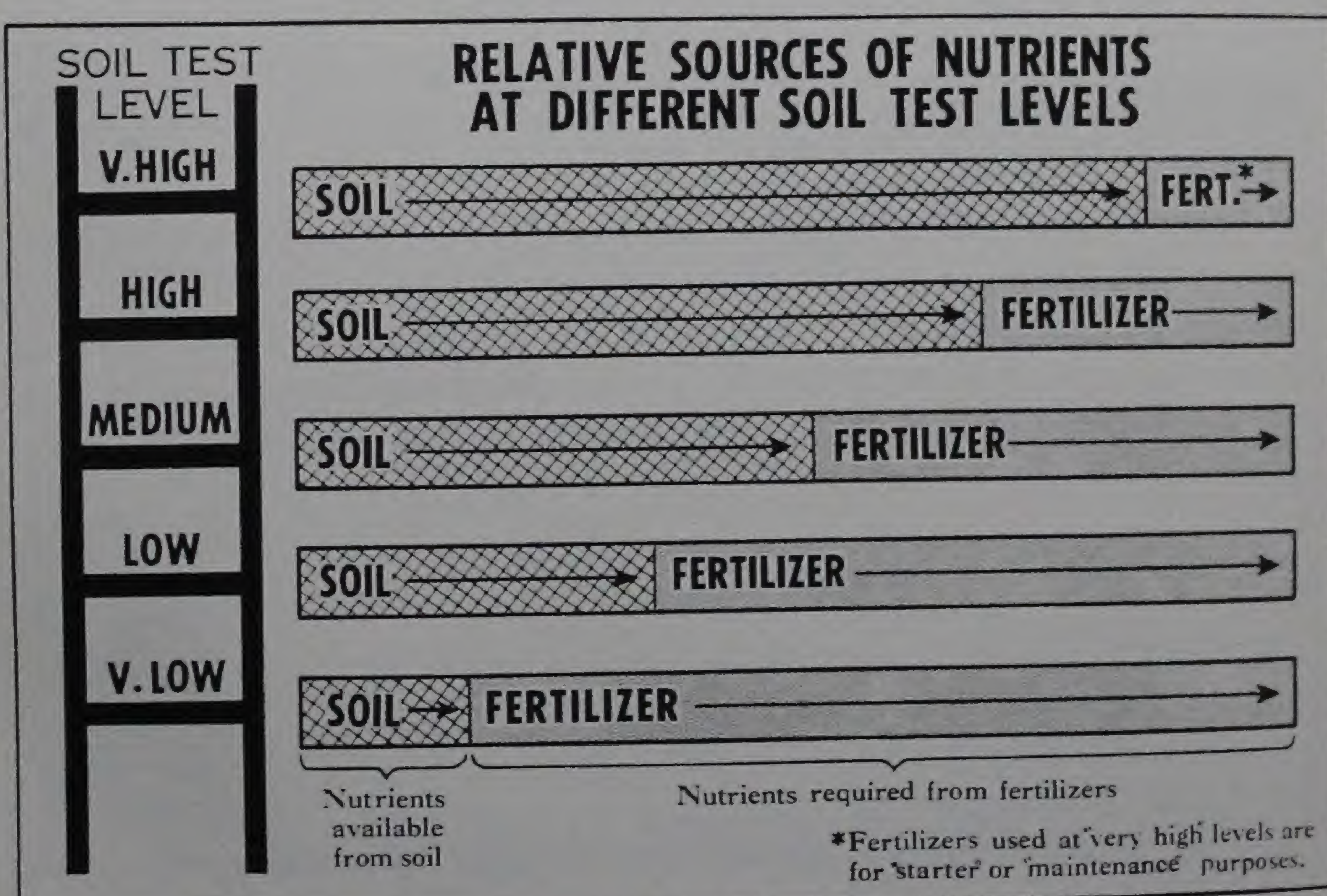
6. Obvious yield differences, with or without leaf symptoms.
7. Poor quality of crops, including unseen chemical composition differences—as in protein, oil, or starch content; and in keeping or storage quality.
8. Yield differences detected only by careful experimental work.

The underground portions of plants have received little attention mainly because of the difficulty in making observations. Development of roots is greatly affected by plant nutrient applications (figures 5 and 6).

SOIL ACIDITY

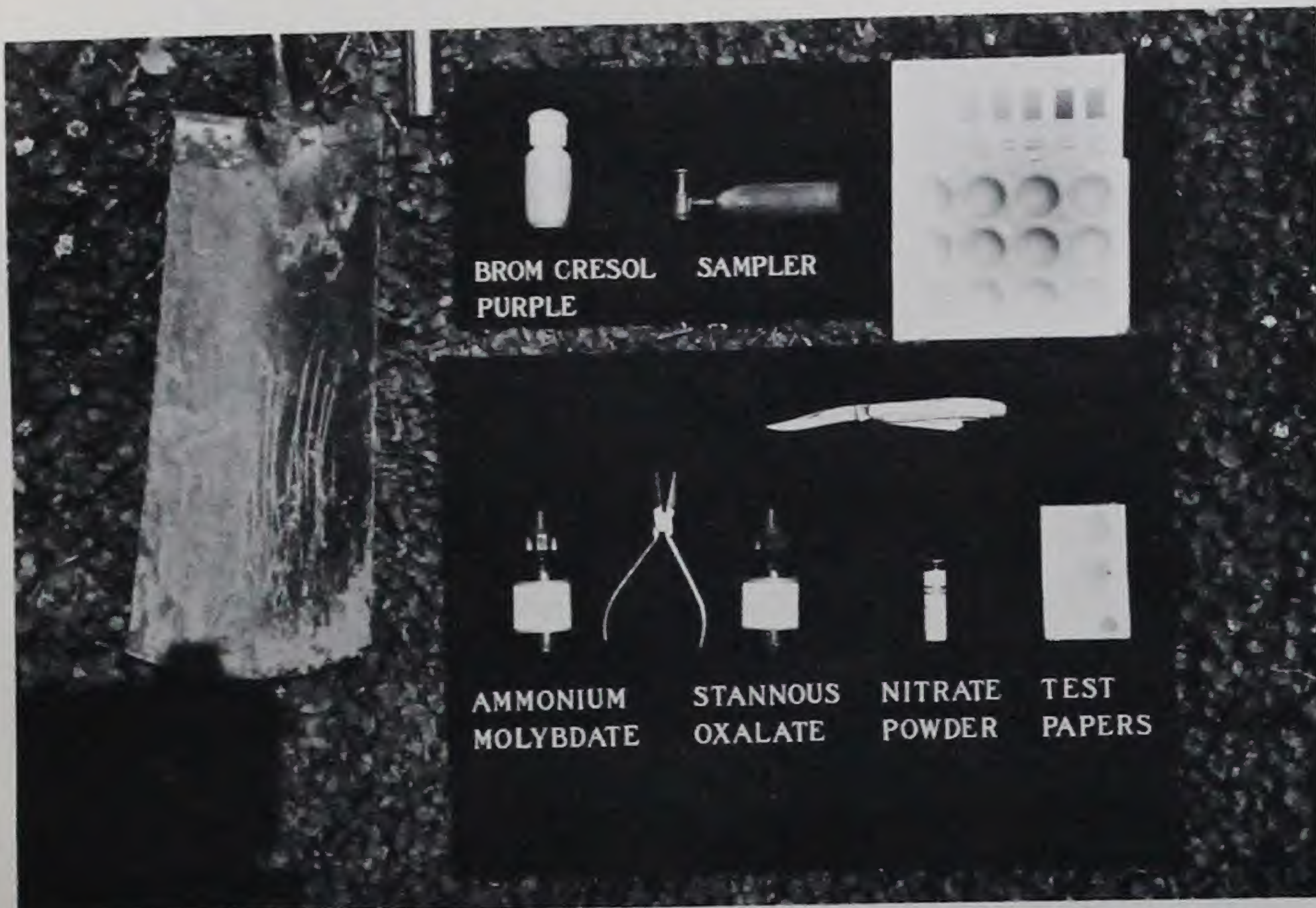
One of the earliest soil treatments that produced observable effects on legumes was application of liming materials to acid soils. This resulted in larger plants having leaves that were darker green (figure 7).

Providing a proper lime level is the first step in any superior soil management program, particularly for legumes. Lime often is called the workhorse in the soil because it has so many functions. Lime adds calcium and magnesium as nutrients. It decreases acidity which has a marked effect on availability of phosphorus and micro nutrients. In



Courtesy of American Potash Institute

Figure 3. The basic principle of soil testing is to determine the proportion of the nutrients needed that the soil can furnish.



Courtesy of American Potash Institute

Figure 4. Tissue testing and soil pH tests in the field are helpful in diagnosing problem areas or in determining fertility status on the spot.

some acid soils a principal benefit of lime is due to the reduction of exchangeable aluminum and/or manganese. Root development is restricted in acid soil horizons and this has been attributed in part to high quantities of aluminum.

Biological effects: Acidity markedly affects the activity of symbiotic nitrogen-fixing organisms (nodule bacteria). Under acid conditions the bacteria cannot function effectively and legumes will be deficient in nitrogen. This is shown by small light green plants with few, if any, nodules on their roots.

Acid soils make for slower decomposition of plant residues and soil organic matter and hence slower release of nutrients. Bacterial counts and activity increase greatly with liming and a more rapid turnover of nutrients contained in residues occurs.

Optimum pH: Needed soil reaction varies considerably with legumes. For alfalfa the soil should generally be in the vicinity of pH 7.0. For soybeans pH 6.2 to 6.5 is generally satisfactory.

Diagnosis: The soil test for pH is reliable. Amounts of lime needed are best determined by a lime-requirement test.

NITROGEN (N) DEFICIENCY

Generally if legumes are to have adequate quantities of nitrogen the proper nodule bacteria must be present on the roots to carry on nitrogen fixation. Several different groups of nodule bacteria are well known, and each group inoculates a given legume or group of legumes. For example, the bacteria that inoculate alfalfa will not function on soybeans.

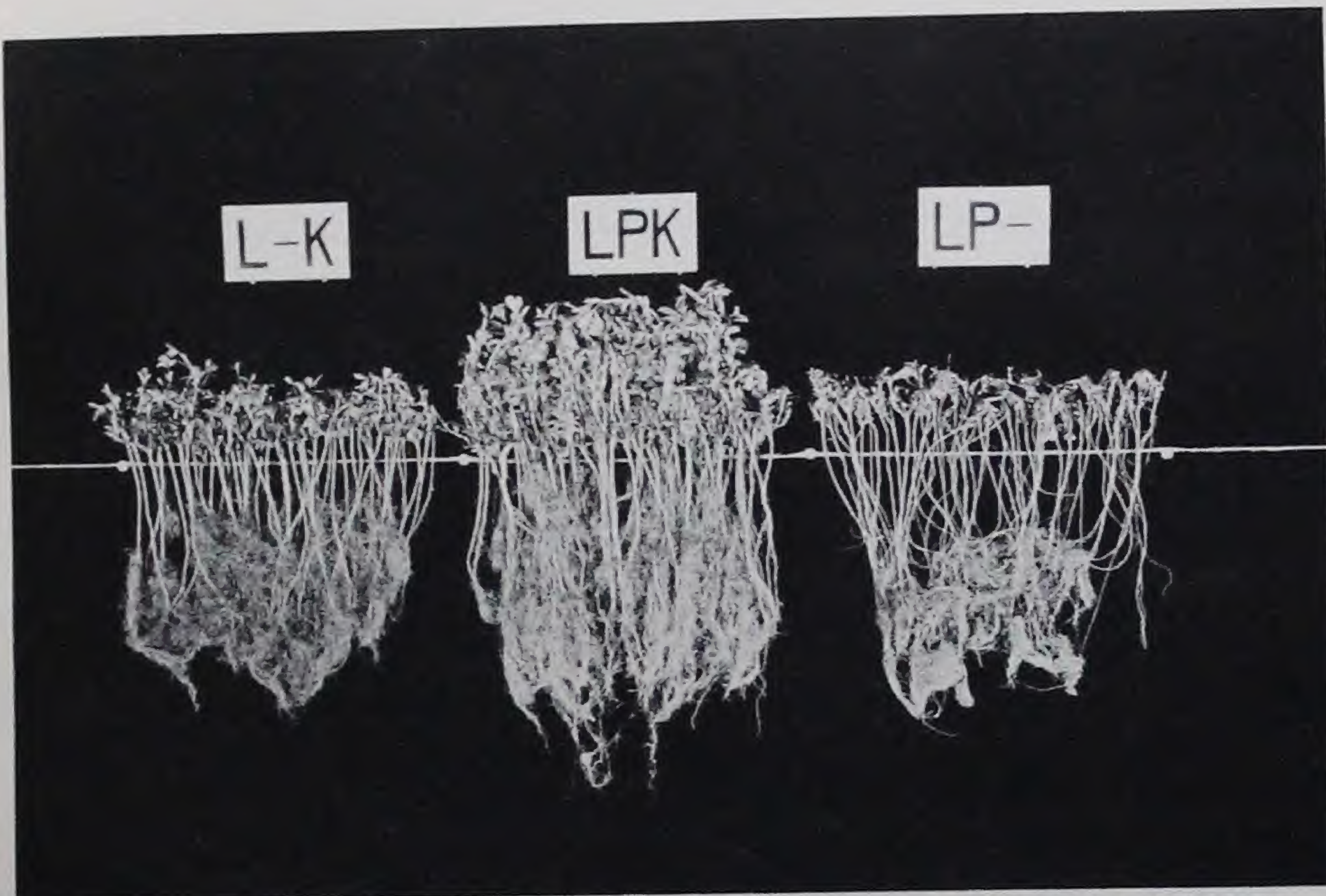
When a new legume is introduced into an area, artificial inoculation is absolutely necessary the first few years it is planted. While buildup of the bacteria takes place in the soil, continued inoculation of legume seed usually is advisable.

Strains of bacteria vary in efficiency. As shown in plate 1, white clover had poor growth with a poor strain of bacteria but good growth with an efficient strain. Inoculation each time a legume is grown helps to provide the most efficient strains available.

Nodule bacteria must have proper conditions in which to work, once they are in the soil. They thrive only within certain ranges of soil reaction and their vigor and effectiveness are lowered with increasing soil acidity. Nodule bacteria differ greatly in reaction requirements, however. For example, alfalfa and sweet clover nodule bacteria function

Courtesy of American Potash Institute

Figure 5. Band placement of a P-K fertilizer directly under the alfalfa seed (left) caused expansion of roots in the fertilizer band. Note unfertilized plants (right).



Courtesy of American Potash Institute

Figure 6. Omission of P or K (left and right) reduced the growth of alfalfa roots and tops the spring after seeding on this soil low in fertility. See heaving of plants. Note the stronger growth of LPK fertilized plants (center).

best around pH 7.0. Soybean and red clover nodule bacteria function satisfactorily at pH 6.2 to 6.5. Liming acid soils is an essential practice in the maintenance of optimum soil reaction for nodule bacteria.

The possibility of inadequate quantities of nitrogen being fixed by the nodule bacteria has been investigated. Application of nitrogen at planting generally is recommended for small seeded legumes such as alfalfa, particularly on light colored soils. The young seedlings may need nitrogen before the nodule bacteria can begin to function.

Applications of nitrogen to established stands of legumes, such as alfalfa, may give small but generally uneconomical responses in yields. Legumes properly inoculated, properly fertilized with phosphorus and potassium, and growing on soil at an optimum reaction generally do not respond to nitrogen fertilizers. However, on acid soils the nodule bacteria cannot function well and a profitable response to nitrogen may be obtained.

As nitrogen fertilizer is added, the efficiency of nodule bacteria is decreased. Also, nitrogen may stimulate grasses and weeds and these

plants may compete seriously with legumes for moisture, nutrients, and light.

Large seeded legumes, such as snap beans, lima beans, and canning peas respond to nitrogen and constitute exceptions. Nodule bacteria do not have the capacity to fix adequate nitrogen for these short-season legumes.

SYMPTOMS

Nitrogen-deficient plants fade in color; this deficiency is indicated when the leaves become pale green with a yellowish-tinge. Later the leaves may become distinctly yellow over their entire surfaces. The deficiency usually appears first on leaves at the bases of plants, but it spreads quickly to upper parts. Progressive stages of nitrogen deficiency on soybeans are shown in plate 2.

Nitrogen-deficient leaves may remain chlorotic for many days while plants make little growth. If not allowed to go too long the green color can be promptly restored by adding nitrogen. Eventually, deficient plants lose their foliage, the lower leaves dropping first.

Diagnosis: Dig up plants to see if roots are well nodulated. Analyze leaves for nitrogen. Sample the soil to determine pH and calcium content.

On acid unfertile soils, liming, adequate fertilization, and artificial inoculation will go a long way toward stimulating the nodule bacteria to fix adequate quantities of nitrogen.

PHOSPHORUS (P) DEFICIENCY

Legumes as a group, have a relatively high phosphorus content. The amount is about the same as sulfur but never as high as nitrogen or potassium. Response to phosphorus often is most marked during the early growth period. At that time plants have limited root systems and depend to a large extent on localized applications. Too, cool soils slow both root development and release of phosphorus from soil organic matter.

SYMPTOMS

Symptoms of phosphorus deficiency are not so well defined as those of many other nutrients. The chief symptoms are retarded rate of growth and spindly plants with small leaflets, the leaves of which turn dark or bluish green. Maturity is delayed.

Response of soybeans to phosphorus at blooming is shown in plate 3. Phosphorus deficient plants tend to be delayed in blooming and in ma-

turity. Phosphorus deficiency results in an upward tilting of leaf blades which may appear to be pointed.

In most legumes the stems also redden under severe deficiency. This color tends to develop if a lack of phosphorus, or any other element, interferes with the utilization and transfer of carbohydrates. The accumulated sugars favor the formation of the reddish pigment, anthocyanin.

A limited supply of phosphorus reduces the number as well as the efficiency of nodule bacteria.

Diagnosis: The dark green leaves of phosphorus hungry legumes often give the impression that the plants are healthy. Soil and plant tests are an aid in determining the level of phosphorus in the soil and the plant. A pH test is important, as acid soils fix phosphorus into unavailable forms. Check to determine if plant roots are able to get applied phosphorus in the soil.

POTASSIUM (K) DEFICIENCY

Potassium deficiency is perhaps the most easily recognized symptom in legumes. Compared to other fertilizer elements, potassium is removed in relatively large quantities either in hay or in seed from large-seeded legumes. Continual growing of legumes on a given field without adequate fertilization depletes the soil of a number of elements, potassium in particular.

On acid soils, liming on one hand tends to conserve potassium because the calcium and magnesium replace some of the potassium which otherwise would be taken up by the plant. On the other hand potassium requirements are increased because of higher yields and greater removals.

SYMPTOMS

Soybeans: Broad-leaved legumes, such as soybeans, show evidence of insufficient potassium in early growth stages by irregular yellow mottling around the edges of their leaflets, particularly in the lower parts of the plants (plate 4). These chlorotic areas then merge to form continuous yellow borders around the tips and along the sides of the leaves. Death or necrosis of the chlorotic areas follows, with a downward cupping of the leaf edges. The dead tissue then falls out, giving the leaflets a ragged appearance. Marginal firing often spreads to include half or more of leaflet areas, while their centers and bases remain green (plate 5). Extreme deficiency of potassium tends to produce wrinkled and misshapen seed. Maturity is delayed.

When the supply of potassium gives out late in the growing period, pronounced chlorosis is less likely to appear. Instead, the upper leaf petioles below the leaflets may turn brown and then the leaflets droop and die.

Alfalfa: Potassium deficiency is one of the common causes of "alfalfa yellows." This condition may be caused by a variety of other factors including deficiency of boron, nitrogen, manganese, or sulfur. It also may be the result of insect injury (plate 17), so that close examination is necessary in order to identify the specific trouble.

With potassium deficiency small white spots first appear around the margins of the leaves (plate 6). The tissue between the spots then becomes yellow and dies. The severity of this marginal yellowing increases progressively from the top of the shoot to the lower leaves. Potassium is mobile within the plant and this explains the more pronounced symptoms on the lower parts, which lose this nutrient to the younger upper leaves.

First cuttings may show little deficiency even on low potassium soils, since over winter some K may be released which is utilized by first crops. The deficiency symptoms may become progressively worse on second and third cuttings. Loss of stands to weeds and grasses may be a hunger sign (figure 8). More alfalfa is said to starve out than to winter-kill. Weeds and grass are better competitors for potassium than is alfalfa. For top production and maintenance of stands 2.0 percent of K or higher in the plant is suggested (dry weight basis).

Peanuts: Peanuts remove large amounts of potassium but actual deficiency symptoms seldom appear on this crop in the field.

Clover: Deficiency in Ladino clover is first shown by the appearance of a few small yellow spots, usually near the margins of the leaflets. The edges later turn yellow. With severe deficiency entire leaf surfaces, with the exception of areas near midribs, may be affected. The symptoms in alsike, red clover, and sweet clover are very much like those in alfalfa and Ladino.

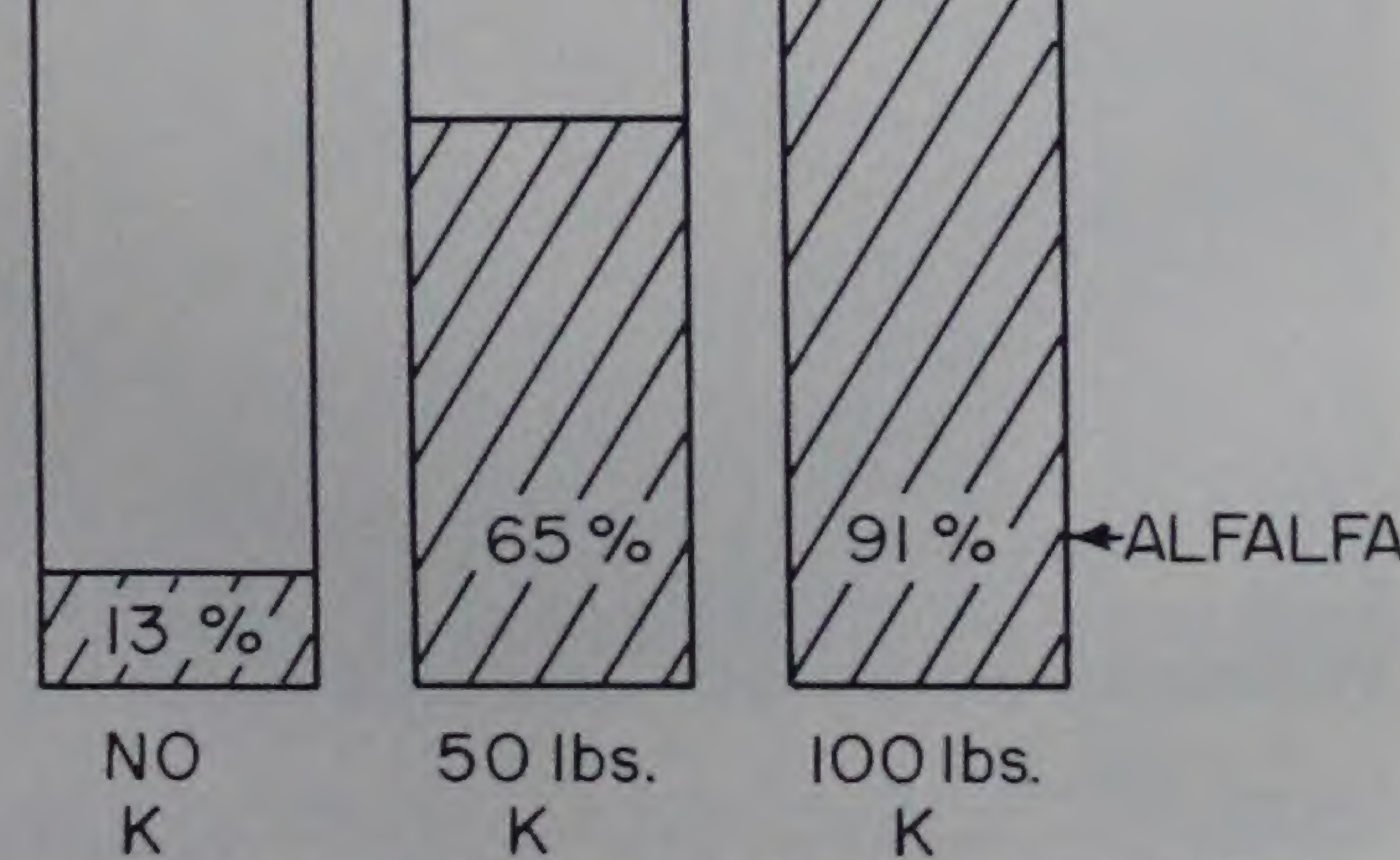
Again, as with alfalfa, in a field of grasses and clovers, if potash is deficient in the soil, legumes will die out, perhaps without showing obvious symptoms. A high level of potassium in both the soil and the plant is necessary to keep clovers in a clover-grass association.

Diagnosis: Plant symptoms can be verified by plant analyses or tissue tests. Soil tests are helpful in identifying critically low levels of available soil potassium and serve as a supplement to plant tissue tests.

Toledo Soil Experiment Field; Courtesy of Illinois Agricultural Experiment Station

Figure 7. Lime produced a marked growth response of soybeans on this acid soil (left). In addition to other benefits the larger leaves take fuller advantage of the energy from the sunlight in photosynthesis. Soybeans on right, without lime, made less growth and yield.

Figure 8. Three years after seeding on a low-potassium soil alfalfa receiving no K was nearly crowded out by weeds and grass. With 100 pounds K per acre (right) alfalfa had a 91 percent stand. Legumes may disappear without deficiency symptoms appearing. Weeds and grasses have greater capacity to absorb K and simply crowd out the legume.



Courtesy of Department of Agronomy, University of Illinois

CALCIUM (Ca) DEFICIENCY

Calcium deficiency symptoms frequently have been produced on legumes in controlled greenhouse experiments. Distinct symptoms rarely are seen under field conditions.

Small seeded legumes are most sensitive to soil acidity and lack of calcium. Such seeds have little reserve of plant nutrients, and the root systems of the seedlings are easily stunted. Perennial plants are apt to succumb to summer drouth and winter killing the first year.

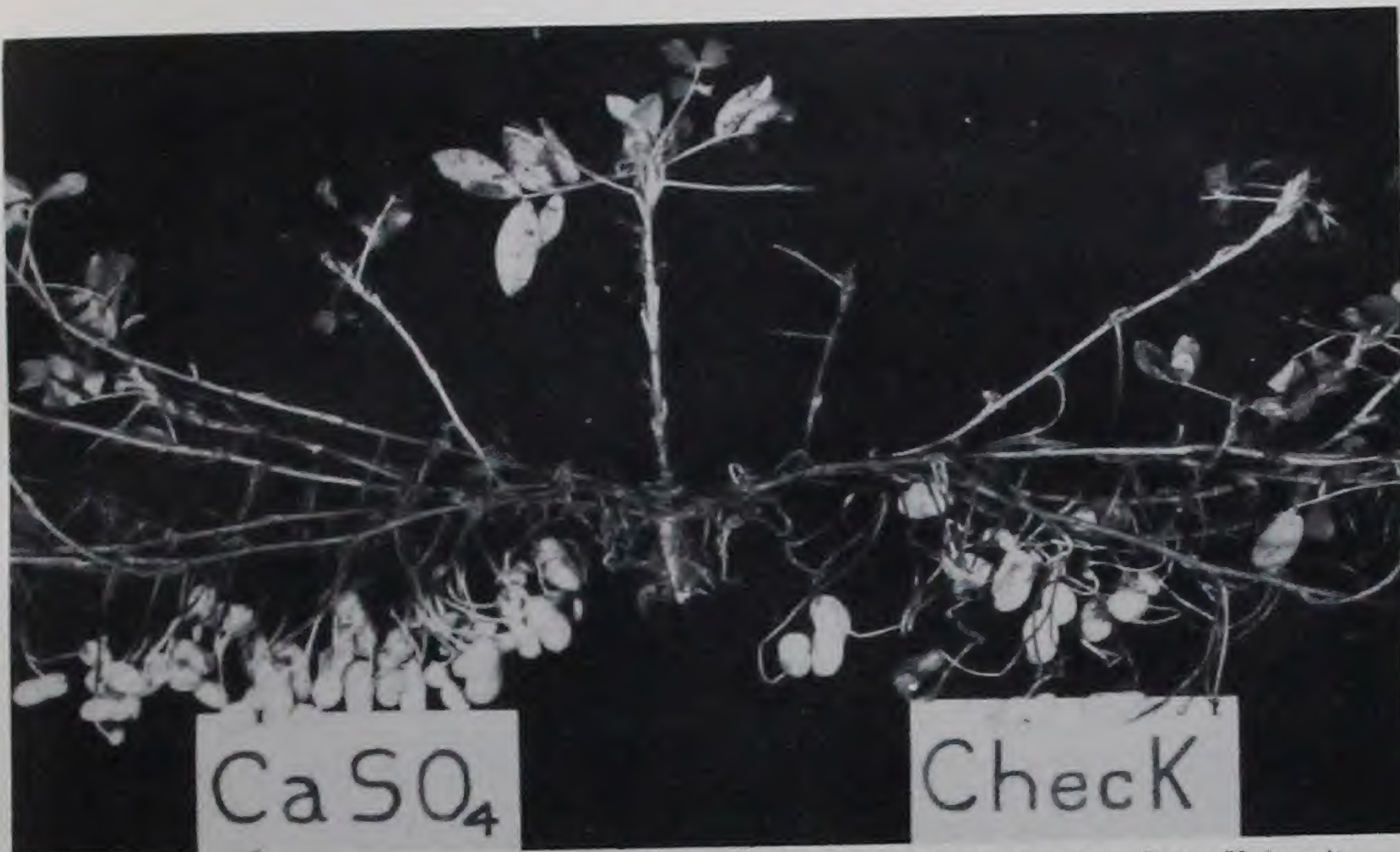
Legumes are relatively high in calcium as compared to non-legumes. Although the functions of calcium are not fully understood, the symptoms indicate that among other roles this element plays a part in cell-wall formation. Weakening of the cell walls causes the sudden collapse of leaf petioles.

SYMPTOMS

Soybeans: In sand culture, emergence of primary leaves on calcium deficient soybean plants is delayed, and when the leaves emerge they

Courtesy of American Potash Institute

Figure 9. Soybeans without lime on this acid claypan soil were small with chlorotic, misshapen leaves (left). These symptoms probably resulted from a combination of calcium deficiency and manganese toxicity.



Courtesy of Department of Agronomy, North Carolina State University

Figure 10. Low calcium in the fruiting zone of large type Virginia peanuts shows at harvest in the form of many pops (unfilled shells). Calcium sulfate was applied on the left.

are cup shaped. Terminal ends of primary leaves become necrotic and narrow chlorotic bands develop around portions that remain. Tissue between the veins tends to ridge. Terminal buds deteriorate and petioles break down. Primary leaves become soft and are dropped. Soybeans grown on acid soil (ph 4.5) are shown in figure 9. The plants were very high in manganese and the effects may be due to manganese toxicity as well as low calcium.

Red clover: Calcium-deficient red clover in sand culture is shown in plate 7. In addition to the collapsing petioles, small white dots distributed irregularly over the entire surfaces of the full-grown older leaves may appear.

Peanuts: With large type Virginia peanuts, a high percentage of pops or unfilled shells at harvest is a sign of calcium deficiency (figure 10). The plants are light green in color.

With the exception of peanuts, the calcium requirement of most crops is taken care of by an intelligent liming program. For peanuts a relatively soluble source of this element may be required in addition to, or in place of, lime in order to insure a high calcium level in the fruiting zone.

MAGNESIUM (Mg) DEFICIENCY

Legumes normally contain two to three times as much magnesium as grasses and, too, they generally contain more magnesium than phosphorus. Magnesium has an important role in chorophyll formation as it is a part of the molecule. Magnesium deficiency hinders nitrogen fixation by nodule bacteria.

Potassium additions tend to decrease uptake of magnesium. Hence, on a soil close to the borderline in available magnesium, high rates of potassium may bring about magnesium deficiency. Deficiency is more likely to occur on acid, sandy soils.

In contrast to calcium, magnesium moves more freely in the plant. Magnesium tends to improve utilization and mobility of phosphorus.

SYMPTOMS

Soybeans: In early stages of magnesium deficiency, the areas between the main veins of leaves of soybeans become pale green. These areas later turn a deep yellow except at the bases of the leaves. Lower leaves are likely to be affected first. Rusty specks and necrotic blotches may appear between the veins and around the edges of middle and upper leaflets.

At late stages of growth, magnesium deficiency gives the general appearance of early maturity. There is a curling downward of the leaf margins, a gradual yellowing from the margins inward, and a bronzing over the entire leaf surfaces.

Peanuts: In sand cultures the older leaves of peanuts become chlorotic at their margins. This chlorosis later advances to midribs and the leaf margins become orange in color.

Red Clover and Alfalfa: Central interveinal chlorosis appears in clover and alfalfa with leaf margins chlorotic in late stage (plate 8).

Applications of dolomitic limestone generally take care of magnesium needs. However, where the soil pH already is high because of calcitic lime additions, or where legumes are grown in a rotation with crops requiring an acid soil, application of magnesium in a soluble form may be necessary to prevent deficiencies.

SULFUR (S) DEFICIENCY

Reports of sulfur deficiency are increasing. Several reasons may be given for this development, although the native supply is continuously replenished by that coming down in rain and snow. Sulfur bearing gases

in the air are chiefly a result of the burning of coal and other fuels. While coal smoke has a particularly high sulfur content, other fuels containing little sulfur are replacing coal. Hence, in the more sparsely populated areas particularly, inadequate amounts of sulfur are being supplied by precipitation.

Formerly, much of the phosphorus in fertilizer was derived from normal superphosphate which contains about 50 percent calcium sulfate. Too, ammonium sulfate and potassium sulfate fertilizers have furnished some sulfur. Although still used in large quantities, normal superphosphate and ammonium sulphate gradually are being replaced by higher analysis materials containing little or no sulfur. Hence, the dwindling sulfur supply requires special attention.

Sulfur is a constituent of a number of plant compounds. Most important of these are various proteins that are valuable in animal nutrition. Sulfur is particularly important in legumes, and total sulfur concentrations in plants may approach or even exceed those of phosphorus.

Alfalfa and clovers have shown marked responses to sulfur on deficient soils. Protein content may be increased even more spectacularly than yields.

SYMPTOMS

With sulfur deficiency, the younger leaves of plants, including the veins, turn pale green to yellow (plate 9). In later stages the older leaves turn yellow. The symptoms are very much like those of nitrogen deficiency, although when nitrogen is limiting, the older leaves tend to be affected first. Plants are small and slender.

Diagnosis: Symptoms of sulfur deficiency are not as readily recognized as those of other elements. They can best be confirmed by sulfate or sulfur application on strips through fields to determine responses in plant growth. Plant analyses are helpful.

DEFICIENCIES OF MICRO NUTRIENTS

Essential nutrients required in extremely small amounts are called micro nutrients. They also sometimes are referred to as trace or minor elements. Even though amounts needed are small, these micro nutrients are just as essential for plant growth as are the major and secondary nutrients. The micro nutrients discussed in this chapter are boron, cobalt, copper, iron, manganese, molybdenum, and zinc.

Several of the micro nutrients have properties in common. With the exception of molybdenum, the micro nutrients generally become less

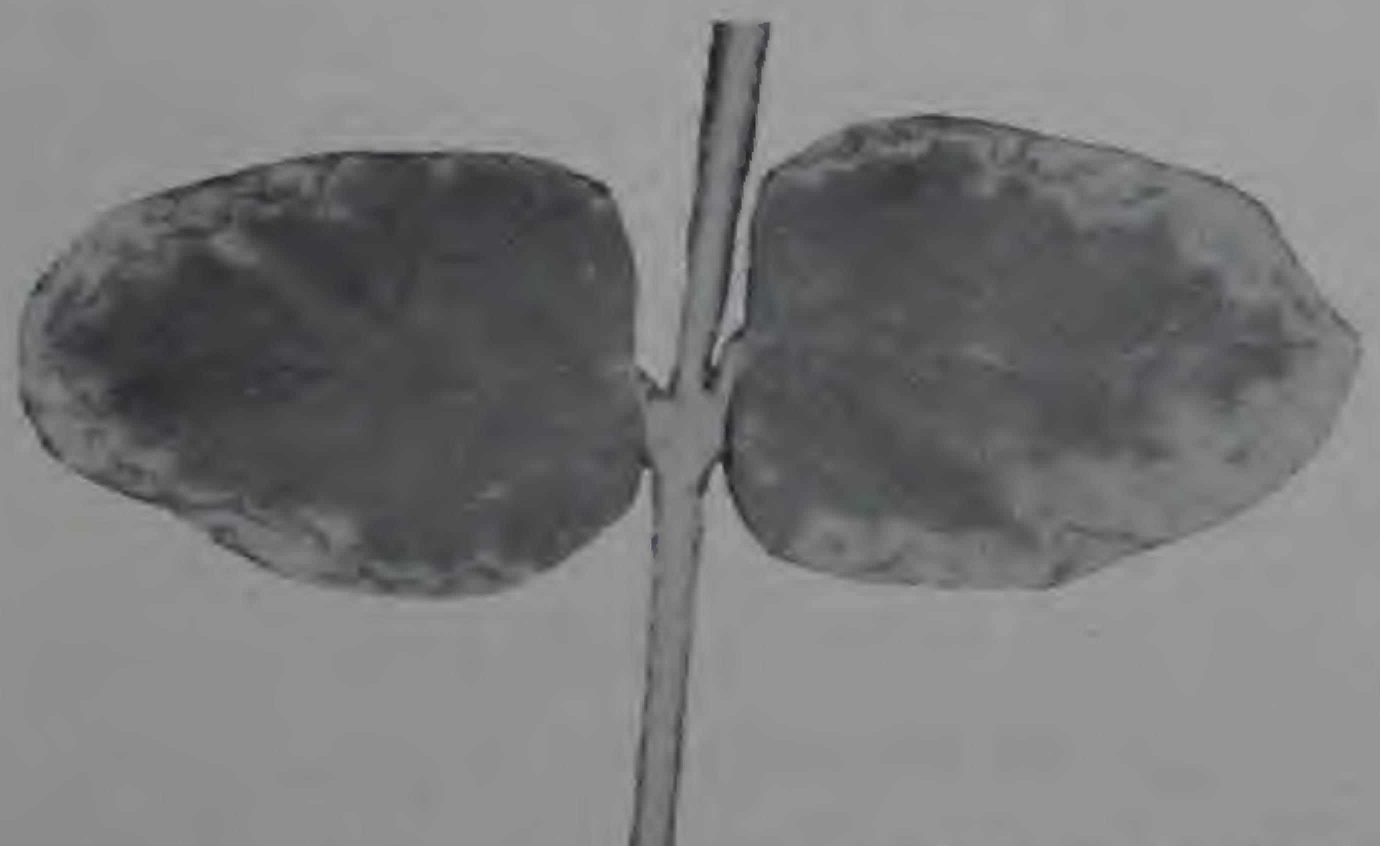
available as the soil pH increases. Molybdenum becomes more available as the pH increases. Hence, molybdenum deficiency occurs on acid soils, while the other nutrients are most commonly deficient on high pH or alkaline soils.

Copper, iron, manganese, and zinc deficiencies occur more often in high organic soils than in mineral soils with low organic content. Muck and peat are organic soils frequently deficient in those nutrients. Deficiencies also occur in sandy soils, and on areas from which the surface soil has been removed by erosion or by land leveling.

The optimum level of any available micro nutrient in the soil is relatively narrow so that toxicity as well as deficiency symptoms may occur. The recommended application of boron for alfalfa usually is about 5 pounds per acre. However, an application of only 0.5 pound per acre at planting near rows of soybeans or peanuts will produce toxicity symptoms and injure such crops (figure 11).

BORON (B) DEFICIENCY

Boron deficiency has occurred on a number of legumes. Among the crops that have shown deficiency symptoms are alfalfa, red clover, Ladino clover, and Korean lespedeza. The plant requirement is low. Healthy alfalfa may have a boron content of 35 parts per million. A 6-ton crop of alfalfa would thus remove only three-eighths of a pound of boron per acre. Although the amount needed is small, some soils are so low in available boron that they cannot supply enough for healthy plant growth.



Courtesy of Dept. of Agron., Ohio State Univ.

Figure 11. Boron toxicity symptoms in soybeans. The narrow margin around the edge of the leaf fires and is very thin.

Boron deficiency occurs most frequently on sandy soils, and on highly weathered residual soils in the more humid regions. Available boron is readily leached from the soil. Much of the boron available in a single season is released from organic matter by microbial action.

SYMPTOMS

Alfalfa: Boron deficiency occurs on alfalfa more frequently than on any other legume crop. The youngest growth is influenced first because boron is relatively immobile in the plant. Deficiency symptoms are

shown in plate 10. The upper internodes of plant stems are shortened and plants develop a rosette appearance. Upper leaves near the growing point turn yellow and sometimes are reddened. The symptoms are more severe at the leaf tips. The lower leaves remain a healthy green color. Flowers fail to form and buds appear as white or light brown tissue. These symptoms frequently occur just before the flowering stage of growth and during periods of dry weather. Severe boron deficiency shows up as white leaves at the tops of plants. Boron deficiency may sometimes be confused with leafhopper damage, potassium deficiency, calcium deficiency, or spittle-bug injury.

Boron deficiency symptoms may occur in spots over the field during drought periods and may be absent in years when rainfall is adequate. Usually the second and third crops of alfalfa are more severely affected than the first.

When boron deficiency symptoms occur yields of hay may not be greatly affected but marked yield responses often occur. Hay quality may be reduced and seed yields greatly reduced even when hay yields are not greatly affected.

Red and Alsike Clover: Boron deficiency symptoms occur as a red coloration, sometimes with a purplish tint, on the margins and tips of the younger leaves of red and alsike clover plants. The coloration gradually spreads over the leaves and the leaf tips may die.

Ladino Clover: Boron deficiency on Ladino clover is shown in plate 11. The younger leaves turn yellow. The edges of some of the leaves later become red and then turn brown and die.

Diagnosis: Symptoms can be verified by plant analyses or soil tests. Plant contents below 20 parts per million indicate possible boron deficiency.

COBALT (Co) DEFICIENCY

Cobalt is an essential element for nodule bacteria on legumes. Deficiency symptoms have been produced in nutrient culture experiments but no plant deficiency symptoms of cobalt have been reported in the field. However, the cobalt content of forage may be quite important to health of livestock (figures 7 and 8, Chapter I).

COPPER (Cu) DEFICIENCY

Copper deficiency is found mainly on peat and muck soils. Some newly developed peat or muck will produce little plant growth until fertilized with copper.

SYMPTOMS

Copper deficiency occurs on the youngest tissue. Growth is reduced in deficient plants and their color changes to grayish-green, blue-green, or olive-green. Their leaves die and their internodes are shortened.

Alfalfa: In alfalfa, the leaves turn to a faded green with a grayish cast (plate 14). Reduced growth and shortened internodes produce bushy plants. Necrotic areas appear on the margins of the upper leaves about one fourth to one half of the distance from the leaf tips. Copper deficient plants are much like those produced under drought conditions.

Clover: Copper deficiency on subterranean clover is characterized by light green plants and the absence of the usual dark markings near the centers of the leaves.

IRON (Fe) DEFICIENCY

Iron deficiency may occur on acid soils that are high in available manganese. The iron-manganese ratio is very important. However, iron deficiency occurs more frequently on high-lime soils because of low availability of iron. In this case, manganese availability is not high and both elements may be deficient.

SYMPTOMS

Soybeans: Iron chlorosis of soybeans is shown in plate 12. In the initial stages the areas between leaf veins turn yellow just as with manganese deficiency. However, as iron deficiency becomes more severe the veins also turn yellow and finally the whole leaf turns almost white. Brown necrotic spots also may occur near leaf edges. The newer leaves are affected. Iron is relatively immobile in the plant so that iron does not move from the older leaves to the newer chlorotic leaves.

Peanuts: The newer leaves become chlorotic. Peanuts are not so sensitive to iron deficiency as soybeans.

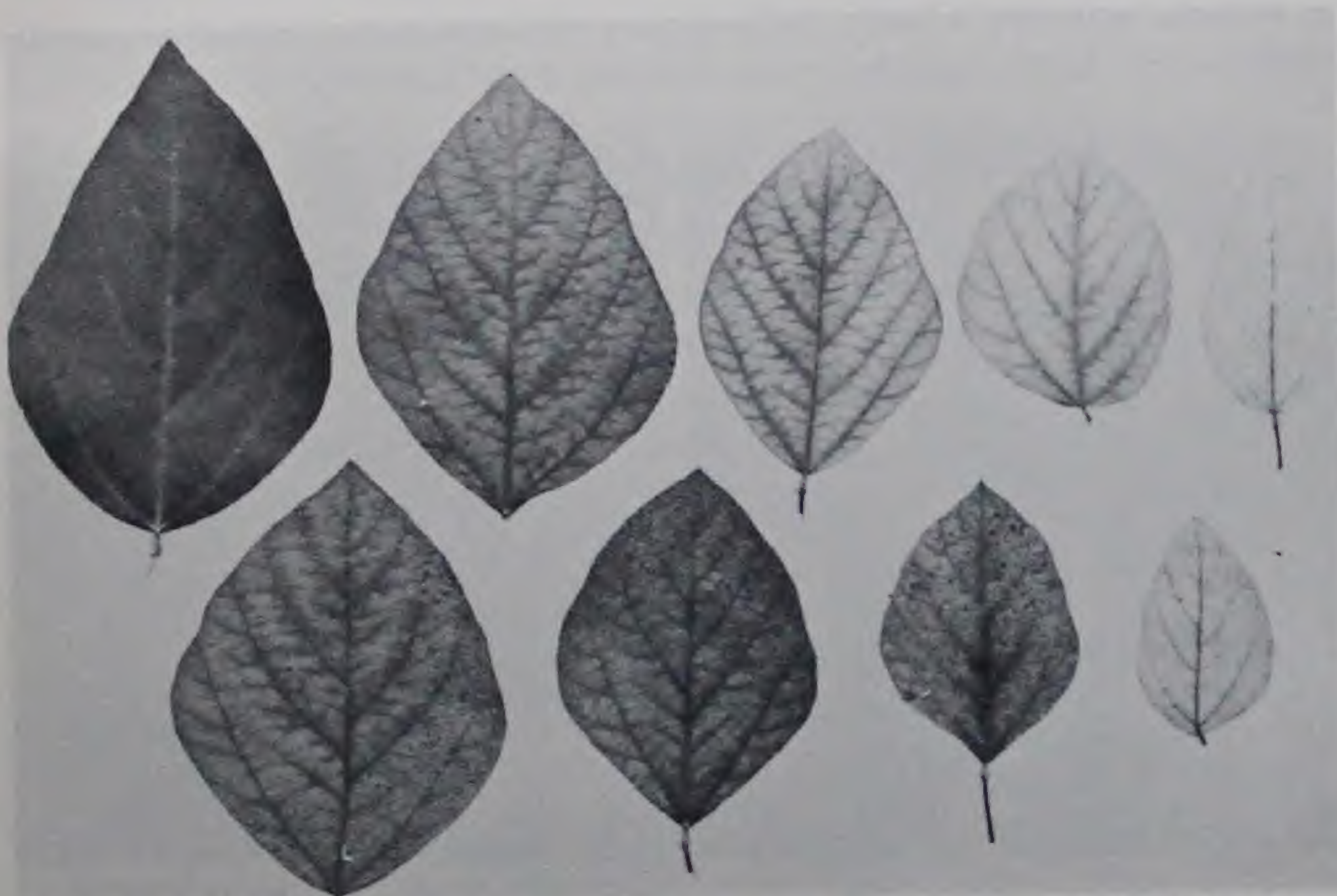
Alfalfa and Clovers: Iron deficiency in these crops is rare and deficiency symptoms have not been described.

Diagnosis: Iron and manganese deficiencies may be distinguished by observation of affected plants that have been sprayed with a 1 percent solution of ferrous sulfate and others with a 2 percent solution of manganese sulfate. Normal color should be restored in 5 to 7 days where the deficient nutrient (ferrous iron) has been applied.

MANGANESE (Mn) DEFICIENCY

Manganese deficiency usually occurs in soils that are low in total manganese and have a pH above 6.2. Manganese availability is low in

alkaline soils, and is reduced by liming acid soils. The deficiency is most common in humid regions in peat and muck soils, in organic sandy soils, and in heavy textured soils that are high in pH. The deficiency usually occurs in depressions in fields. Frequently a very slight reduction in elevation causes an increase in pH which results in a manganese deficient area.



Courtesy of Department of Agronomy, Purdue University

Figure 12. Manganese deficiency causes inter-veinal chlorosis of the soybean leaves. The newer leaves are usually the most deficient.

SYMPTOMS

Soybeans: Manganese deficiency on soybeans is shown in plate 13. The leaves first become chlorotic in their inter-veinal areas while the veins remain green. Whole leaves, veins excepted, become pale green and then pale yellow. Brown spots, necrotic areas, develop as the deficiency becomes more severe.

Manganese deficiency of soybeans differs from iron or magnesium deficiency in that the veins remain green, and stand out prominently (figure 12). The deficiency occurs on the newer leaves. However, because of a change in weather conditions, or because the roots may grow into more acid soil having more available manganese, later leaves may de-

velop having a healthy green appearance. The chlorotic leaves will remain chlorotic but will no longer be at the tops of the plants.

Peanuts: Leaves of manganese deficient peanut plants become chlorotic but the veins do not remain as green as with soybeans. In early stages, the chlorosis appears as a pale yellow coloration between the veins. Later in the growing period, the chlorosis appears definitely bronzed.

Alfalfa and Red Clover: Manganese deficiency symptoms on alfalfa and on red clover once were reported on heavily limed Collington loam

Courtesy of Department of Soils, University of Wisconsin

Figure 13. Molybdenum deficiency in soybeans (left). Molybdenum is necessary for nodulation of roots of legumes (right).

in New Jersey. Both crops were very stunted in growth and their leaves showed marked interveinal chlorosis. Application of 50 pounds of manganese sulfate per acre restored the plants to their normal color and growth. This instance is an unusual case, as alfalfa and red clover rarely are manganese deficient.

Diagnosis: Manganese deficiency can be corrected in most legumes by spraying the leaves with a 2 percent solution of manganese sulfate. Normal color usually is regained in 3 to 7 days.

MOLYBDENUM (Mo) DEFICIENCY

Molybdenum deficiency has been diagnosed on many legumes. Molybdenum is needed by nodule bacteria in the process of nitrogen fixation

from the atmosphere. Molybdenum also is needed for nitrogen assimilation in the plant. Smaller amounts of molybdenum are required for assimilation, so most deficiencies are related to a reduced rate of nitrogen fixation. Molybdenum deficient plants are similar to nitrogen deficient plants, since they both lack nitrogen due to inability of the nodule bacteria to meet requirements (figure 13).

Molybdenum deficiency occurs on acid soils because molybdenum is less available under conditions of low pH. This deficiency usually is related to soil type and often can be corrected by liming. Some types of soil have smaller amounts of available molybdenum than others even though they have the same total amount of this element.

SYMPTOMS

Alfalfa: Molybdenum hungry alfalfa is pale green and has reduced growth. Its lower leaves may die and drop off prematurely. The symptoms are similar to nitrogen deficiency.

Soybeans: Soybeans showing no deficiency symptoms in the field have responded to molybdenum applications in Indiana. By growing second generation soybean seedlings in molybdenum deficient nutrient solutions, deficiency symptoms were observed. The leaves were necrotic and twisted on their stems. They were pale green and had necrotic areas adjacent to their midribs, between their veins, and along their margins. Symptoms on soybeans with adequate nitrogen are shown in plate 16.

Clover: Clovers turn pale green and the leaves become chlorotic as molybdenum deficiency becomes more severe (plate 16, upper).

Peas: Foliage is pale green and vine growth of molybdenum deficient peas is reduced.

ZINC (Zn) DEFICIENCY

Zinc deficiency occurs under a wide variety of soil conditions. Additions of lime and phosphorus may reduce zinc availability and cause deficiencies to occur. Zinc deficiency is more common in regions of limited rainfall where the surface soil has partly or entirely been removed by erosion or by leveling of land for irrigation. Deficient soils are more likely to be alkaline and are likely to contain lime. This deficiency may occur in spots in fields, particularly where newly leveled as in irrigation projects.

SYMPTOMS

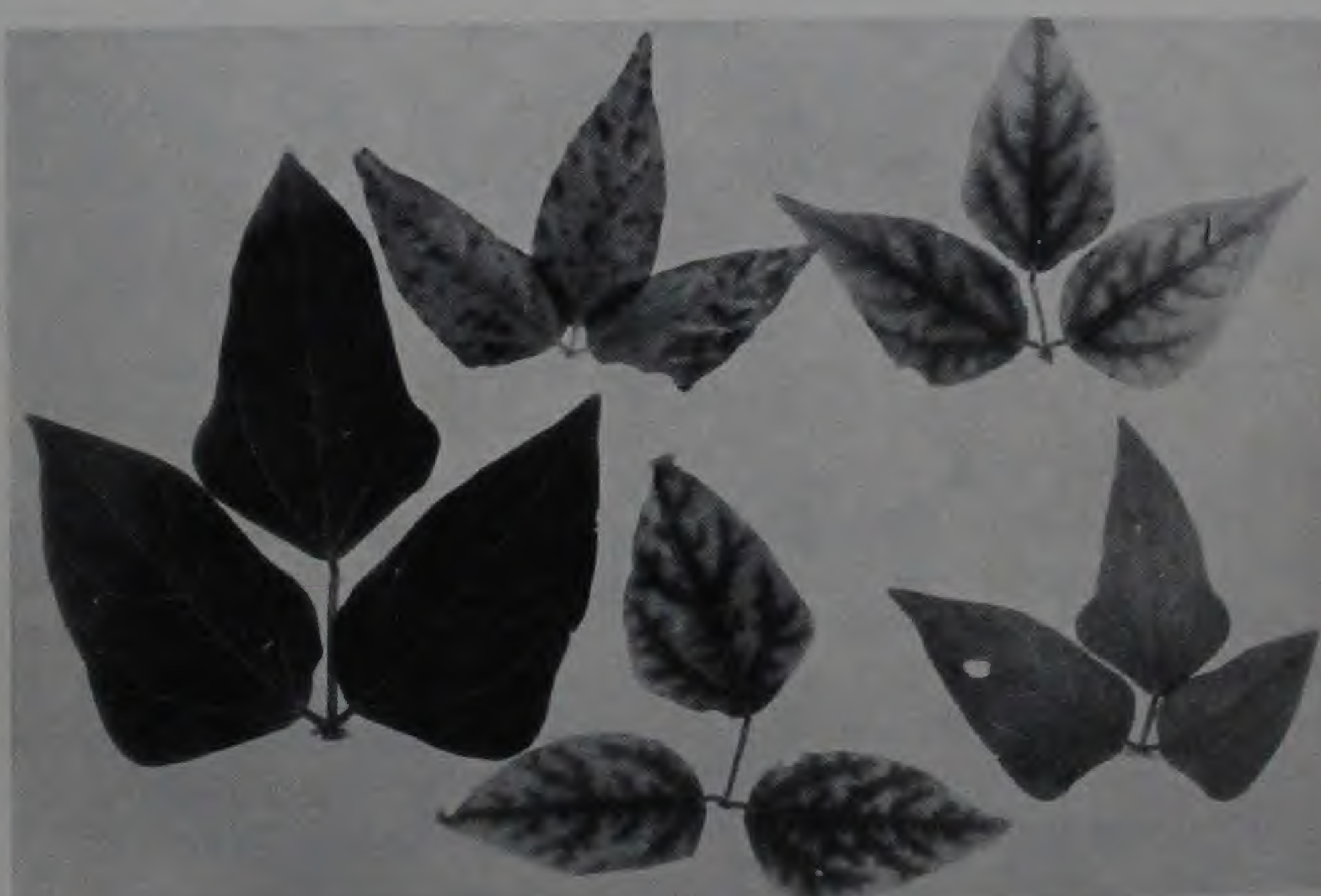
Soybeans and Beans: Zinc deficient plants fail to develop to natural size. The interveinal areas of the leaves become yellow and chlorotic,

the chlorosis being more severe on the lowest leaves (plate 15). The chlorotic tissues may turn brown or grey and die prematurely. A zinc-deficient area in a soybean or bean field will be yellowish-brown in color when viewed from a distance. Maturity will be delayed and few pods produced.

Alfalfa and Clover: While zinc deficiency symptoms rarely occur in alfalfa or clover, this element is important in seed production. The first symptoms of zinc deficiency are bronze-colored spots around the margins of upper leaves. Subsequently, these bronzed areas become white and necrotic (dead). At a later stage the bronze spots become scattered over entire surfaces of leaflets.

Cowpeas: Zinc-deficient cowpeas develop small brown spots on their lower leaves. Interveinal areas become chlorotic and veins remain green. Tissue in the brown spots may die and edges of the leaves may become crinkled (figure 14).

Peanuts: Responses by peanuts to applications of zinc-bearing compounds have occurred but no deficiency symptoms have been observed on peanuts grown on soils where cowpeas have shown a deficiency.



Courtesy of Citrus Experiment Station, University of Florida

Figure 14. Zinc deficiency in cowpeas. Healthy leaflets (left). Various stages of deficiency (right). The leaf tissue between the veins becomes yellow and the area along the veins remains green.

Diagnosis: Where foliar applications of a 1 percent solution of zinc sulfate induce healthy plant growth, a deficiency of this element is likely to prevail. This is an effective means of determining if the deficiency symptoms are induced by low zinc availability. Plant analyses are helpful also.

NUTRIENT CONTENT OF LEGUMES FOR GRAIN AND FORAGE

Chemical analyses of plant tissues are becoming an important means of diagnosing nutrient deficiencies, particularly with the widespread use of spectrographic analysis. Comparison of the chemical composition of healthy and deficient plants often indicates the nutrient that is suspect. A knowledge of normal contents of elements and contents below which a deficiency may occur also is helpful.

Values are given in the list which follows for average nutrient contents of healthy plants and contents below which deficiencies may occur. Values are not shown for all nutrients because of lack of information. Nutrient values for soybeans are for aboveground portions of plants at the bloom stage. Those for alfalfa are for aboveground portions at the one-tenth bloom stage:

Nutrient	Alfalfa		Soybeans	
	Healthy	Deficient when below	Healthy	Deficient when below
	per cent			
Calcium	2.2	1.8	1.5	0.8
Magnesium	0.7	0.3	0.6	—
Nitrogen	3.0	—	2.7	—
Phosphorus	0.3	0.23	0.3	0.2
Potassium	2.3	1.8	2.5	2.0
Sulfur	0.3	0.2	0.25	—
	parts per million			
Boron	35	20	40	20
Manganese	40*	—	35	15
Iron	40*	—	100*	—
Copper	20*	10*	25*	—
Molybdenum	2	0.5	2	0.5
Zinc	40	15	30	20
Cobalt	0.2	—	—	—

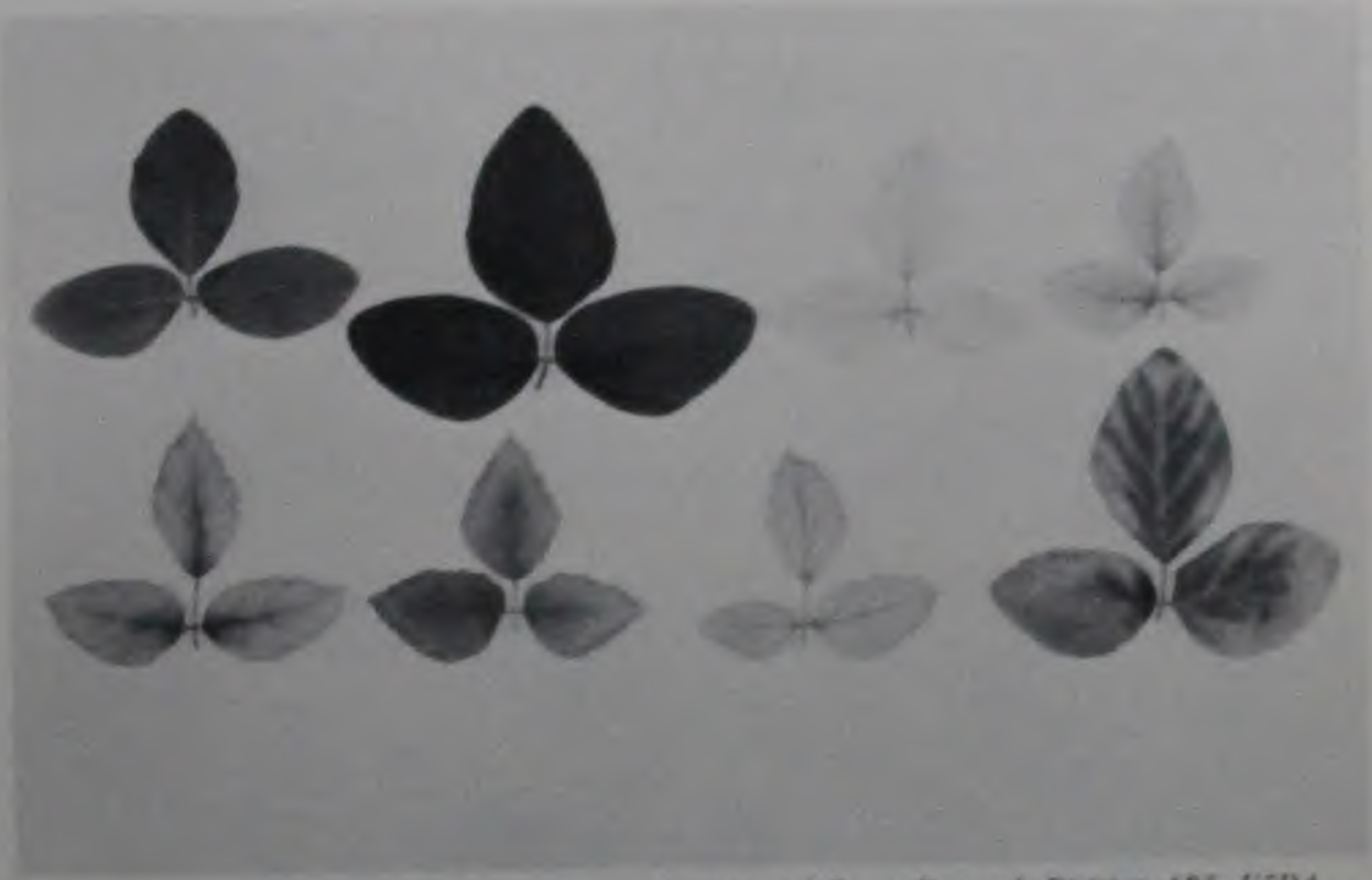
These values are tentative and may be adjusted as more research is done. Those marked with an asterisk are based on limited data. Contents of some nutrients in healthy plants vary widely from the values given. These are the values reported most frequently in the literature. Blanks indicate that data are not available.

NON-NUTRITIONAL SYMPTOMS

Insect damage: Considerable care must be exercised in diagnosing nutrient deficiency symptoms if they are not to be confused with insect damage (plate 17). Leafhopper damage is especially confusing. The

leafhopper punctures the midrib of the leaf and the resulting yellow or red discoloration is in the form of a "V". The apex represents the point of feeding (plate 17, left). In alfalfa this "V" type of yellowing or reddening provides one of the best means of recognizing leafhopper injury.

Spots that are caused by the garden flea beetle on alfalfa sometimes may be mistaken for the beginning of potassium deficiency. However,



Courtesy of Crops Research Division ARS, USDA

Figure 15. Symptoms of bacterial-induced chlorosis in soybeans. Top row (left to right) N deficient leaf, normal leaf, chlorotic leaves. Bottom row, leaves with varying degrees of chlorosis. Leaf on right is in advanced stage of recovery.

such spots are not concentrated on leaf margins and yellowing does not develop between the spots.

Thrip damage often gives rise to peculiar malformations on peanuts early in the growing season (plate 17, right). Applications of DDT usually solve this problem.

Bacterial induced chlorosis: An upper leaf chlorosis occurs on certain varieties of soybeans when inoculated with certain strains of nodule bacteria. This chlorosis always is restricted to new growth and the dividing line between normal and chlorotic portions of the plant is very distinct. In color, this chlorosis varies from almost white to a mottled

yellow-green (figure 15). In severe cases the axillary buds at lower nodes may develop into profuse leaves or branches and the new growth is chlorotic.

A characteristic of this field chlorosis is its rapid onset, persistence of the symptoms for one or two weeks, and then recovery.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF LEGUMES

Element Deficient

I. Effects spread throughout entire plants or confined to older or lower leaves.

A. General on whole plant; also yellowing and drying up or firing of lower leaves.

1. Plant light green. Lower leaves affected first but other leaves soon follow. Lower leaves fade to pale yellow then brown with later shedding. Stunted growth. Due to lack of nitrogen fixation by bacteria. . . . . . Nitrogen

2. Plant dark green. Petioles and leaflets tilted upward. Plants spindly and stunted. Stems may turn red. . . . . . Phosphorus

3. Plant light green. Lower leaves die and drop off prematurely. . . . . . Molybdenum

B. Localized, occurring as mottling or chlorosis with or without spots of dead tissue on lower leaves; little drying up of lower leaves.

1. Areas between main veins become pale green which later turn deep yellow. The base and lower center of the leaf are not affected. Deficiency appearing at a late stage of growth is shown by a downward curling of leaf margins, a gradual yellowing from the margin inward and bronzing. . . . . . Magnesium

2. Yellow mottling around the edges of the leaf. Chlorotic areas merge forming a rather distinct, continuous yellow border around the tip end and along the sides of the leaf. This area soon dries and the dead tissue falls out. In small-leaved legumes there is a tendency for leaves on all parts of the plant to be affected with small white spots appearing around the leaf margins first. Stunted growth. . . . . . Potassium

3. Brown spots develop with yellowing of the leaf tissue between the veins. Dead tissue drops out of chlorotic areas. Stunted growth . . . Zinc

II. Effects localized on newer leaves of plant; stunted growth.

A. Terminal bud dies following distortions at the tips or base of young leaves.

1. Leaves near the growing point yellowed and sometimes reddened. Lower leaves remain healthy green color. Internodes shortened forming a rosette. Buds appear as white or light brown dead tissue. Little flowering . . . . . . Boron

2. Emergence of primary leaves delayed and leaves when emerged are cup shaped. Primary leaves necrotic and narrow chlorotic bands develop around remainder of leaves. Terminal buds deteriorate and petioles break down. . . . . . Calcium

B. Terminal bud remains alive.

1. Leaves light green to yellow with all veins remaining distinctly green. Spots of dead tissue appear on the leaves. Heavy rains may cause chlorosis in young leaves to disappear. . . . . . Manganese

2. Leaves yellow to almost white with principal veins remaining green. Spots of dead tissue appear particularly at the leaf margins. Tissue drops away. . . . . . Iron

3. Leaves including veins turn pale green to yellow. Young leaves affected first. . . . . . Sulfur

4. Young leaves may wilt and wither without chlorosis. Excessive leaf shedding occurs. . . . . . Copper

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Courtesy of Division of Soil Management and Irrigation, BPISAE

Plate 1. Proper nodule bacteria must be present for good growth. The white clover in both pots was inoculated: (right) a poor strain of bacteria was used, note the yellow and dying plants; (left) an efficient strain of bacteria was used.

Courtesy of U. S. Regional Soybean Industrial Products Laboratory

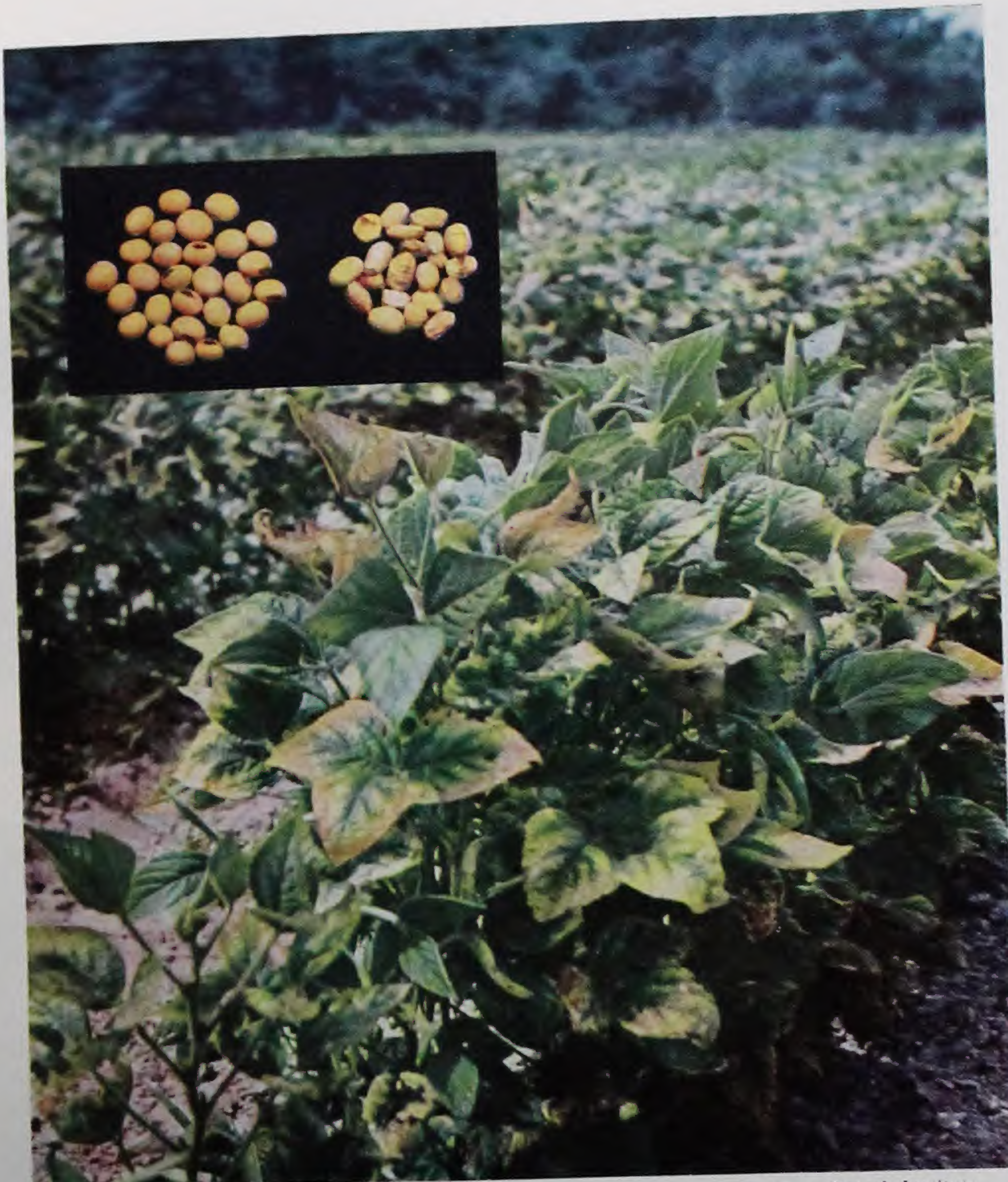
Plate 2. Nitrogen deficiency symptoms in soybeans. Progressive stages of nitrogen deficiencies are shown. The plants were grown in gravel culture under controlled conditions.

Courtesy of Department of Agronomy, North Carolina State College

Plate 3. Growth response of soybeans to phosphorus at blooming on a soil low in phosphorus: (left) no phosphorus added; (right) 17 pounds P—equal to 40 pounds (P_2O_5) per acre. Lime and potassium were added to both rows.

Courtesy of Department of Agronomy, University of Illinois

Plate 4. Potassium deficiency symptoms in soybeans. These begin with yellow mottling, then form continuous bands along sides and tips of leaves.

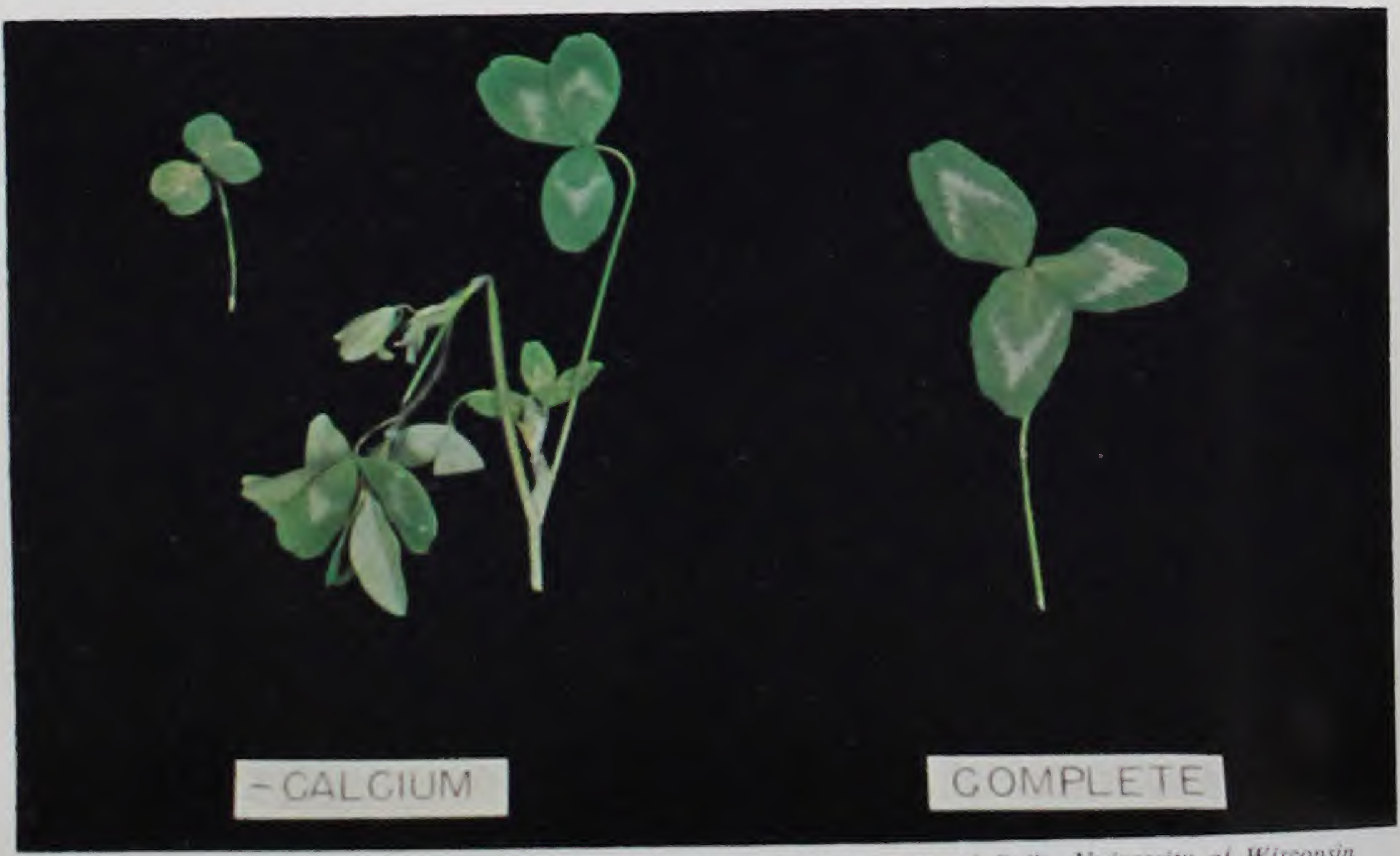


Courtesy of American Potash Institute

Plate 5. Potassium deficiency symptoms in soybeans. In advanced stages the chlorosis proceeds inward and the margins of the leaves fuse to a medium brown color. The center of the leaf still may be green after the margin is completely dead. Seeds are wrinkled and misshapen.

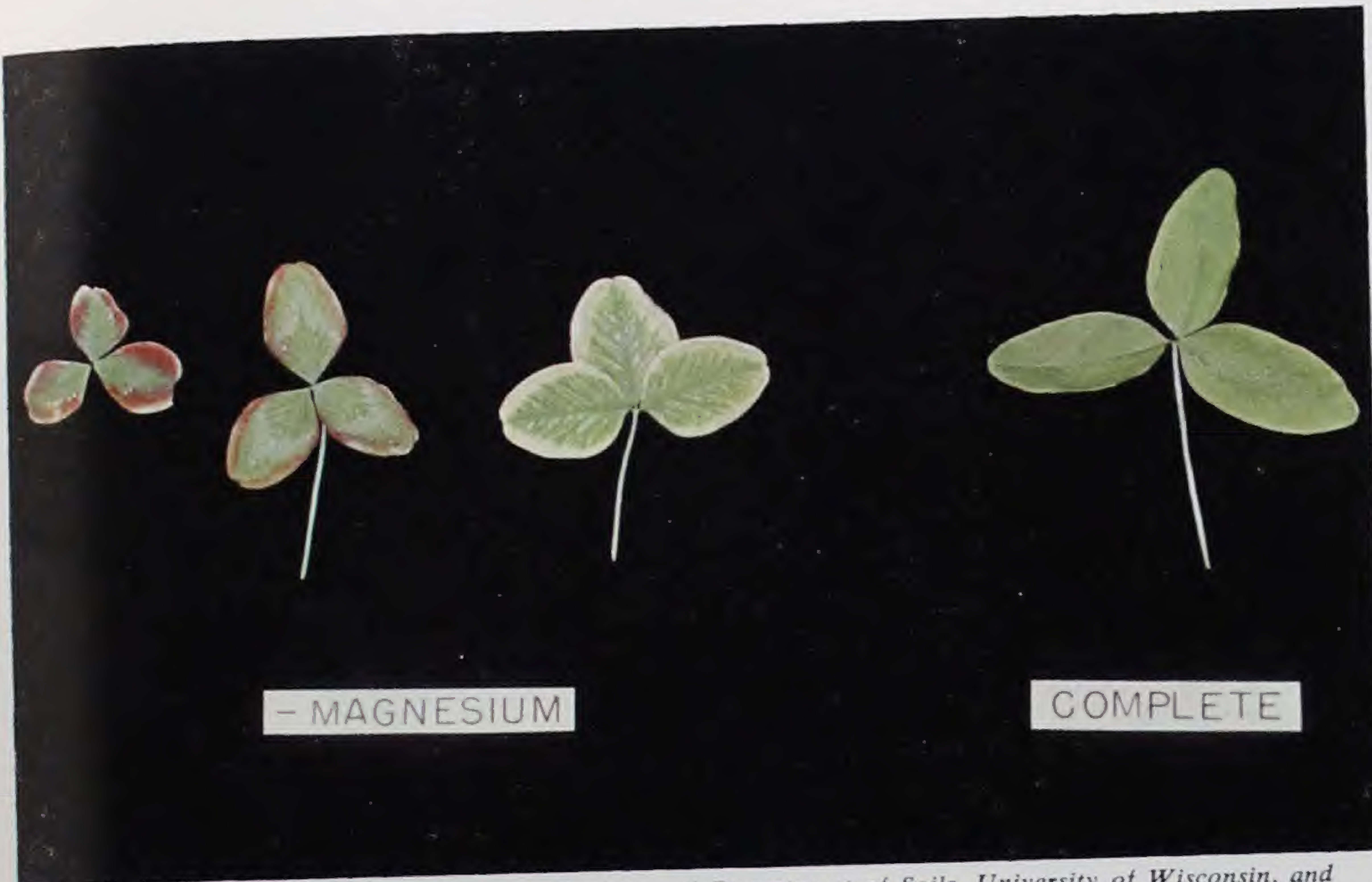
Courtesy of American Potash Institute

Plate 6. Potassium deficiency symptoms in alfalfa. These begin as small white spots around margins of the leaves. In later stages, the tissue between spots becomes yellow, turns brown, and edges of leaves become broken and ragged.



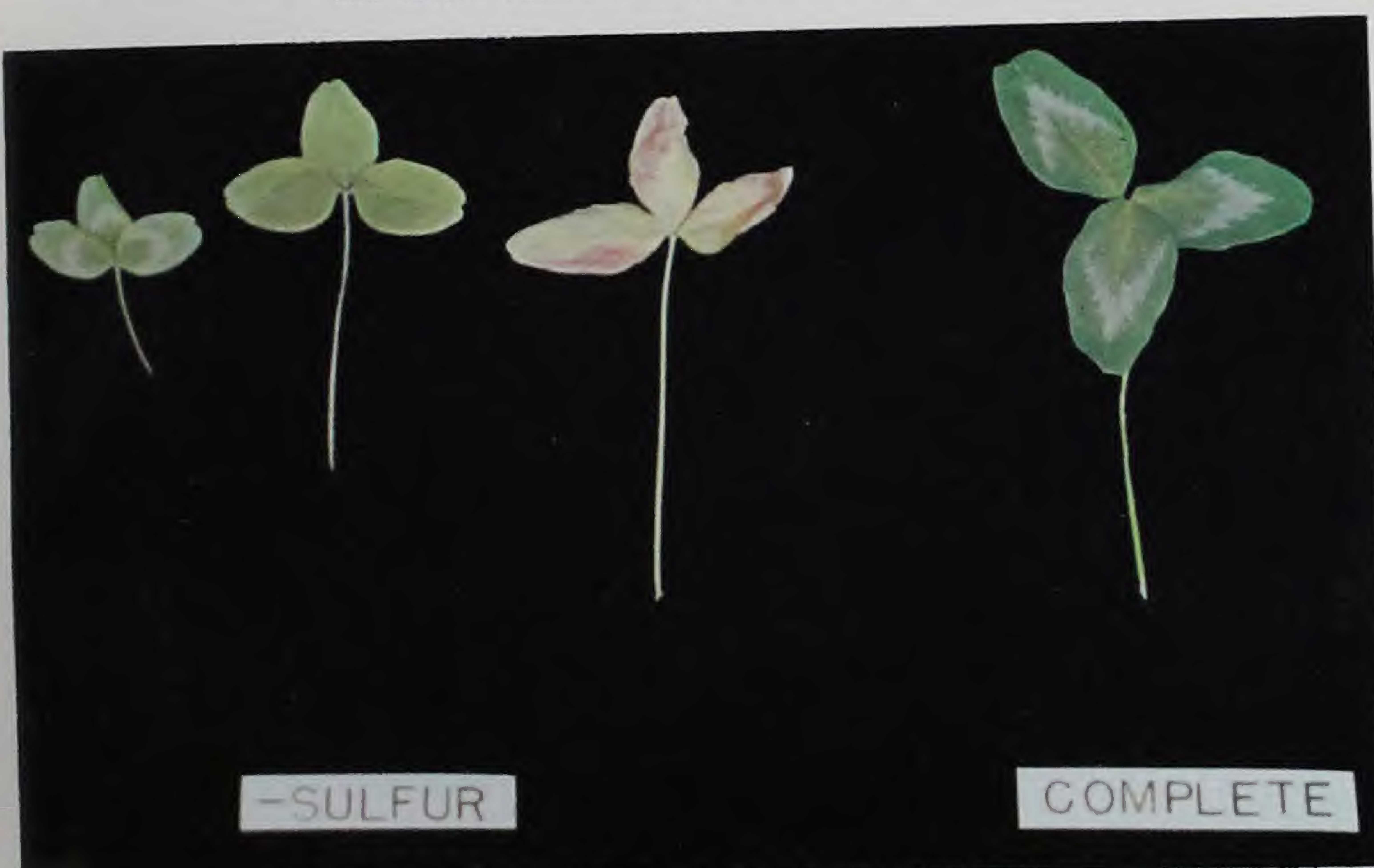
Courtesy of Department of Soils, University of Wisconsin

Plate 7. Calcium deficiency symptoms in clover. Petioles collapse but leaf blades remain turgid for some time before wilting occurs.



Courtesy of Department of Soils, University of Wisconsin, and International Minerals and Chemical Corporation

Plate 8. Magnesium deficiency symptoms in red clover. Leaves become chlorotic between veins and severe chlorosis may occur on leaf edges.



Courtesy of Department of Soils, University of Wisconsin

Plate 9. Sulfur deficiency symptoms in red clover are shown first by the younger leaves, including the veins, which turn pale green to yellow. Necrosis follows.

Courtesy of American Potash Institute

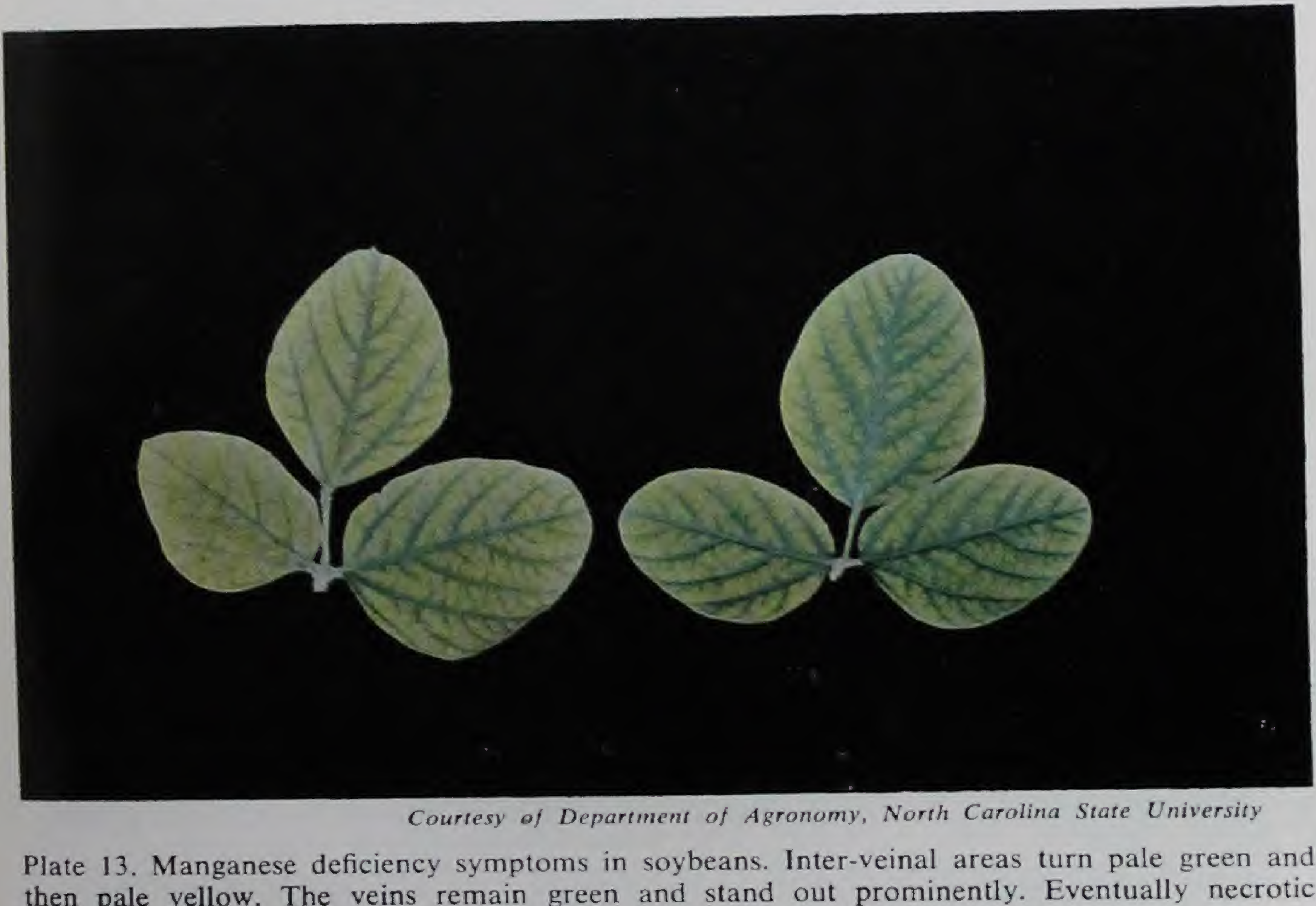
Plate 10. Boron deficiency symptoms in alfalfa. Leaves near the growing point are yellowed and sometimes have a reddish tinge, or they may appear rosetted. Lower leaves remain a healthy color.

Courtesy of Department of Agronomy, Purdue University

Plate 11. Boron deficiency symptoms in Ladino clover. Margins of leaves turn yellow then take on a reddish tinge. Edges of leaves later turn brown and die.

Courtesy of American Potash Institute

Plate 12. Iron deficiency in soybeans. Inter-veinal areas first turn yellow and veins remain green. Later the veins also turn yellow. Finally the leaves turn almost white.



Courtesy of Department of Agronomy, North Carolina State University

Plate 13. Manganese deficiency symptoms in soybeans. Inter-veinal areas turn pale green and then pale yellow. The veins remain green and stand out prominently. Eventually necrotic brown spots occur on the leaves.

Courtesy of Department of Soil Science, Michigan State University.

Plate 14. Copper deficiency in alfalfa. Left, normal leaf. Center, deficient leaves. Right, severe deficiency.

Courtesy of USDA Agricultural Research Service

Plate 15. Zinc deficiency in soybeans: (left) three zinc deficient soybean leaves; (right) a normal leaf in the same stage of growth.

Courtesy of Department of Soils, University of Wisconsin

Plate 16. *Upper.* Right—Molybdenum deficiency symptoms in red clover in presence of adequate nitrogen. Left—Adequate molybdenum. Both grown in water cultures. *Lower*—Progressive symptoms of molybdenum deficiencies in soybeans.

Courtesy of Department of Agronomy, North Carolina State University

Plate 17. These symptoms are not signs of nutrient deficiency: (left) leafhopper injury on crotalaria—note the characteristic yellow "V" at the tip of the leaves, a condition that often is widespread in alfalfa and peanuts; (right) thrip injury in peanuts, a type of malformation occurring early in the growing period.

Chapter VI

Nutrient Deficiencies in Forage Grasses

By W. W. Woodhouse, Jr.*

FORAGE GRASSES constitute a very large and diverse group of plants. Included are annuals and perennials, tall species and short species, bunch types and sod formers. Some do most of their growing in cool seasons and others in warm seasons, and some are high producers and some are low producers. Contrasts in size, growth habit, composition, geographic area of adaptation, and usage, such as occur between Kentucky bluegrass grown for grazing above the Arctic Circle and elephant grass cut for green fodder under the Equator are not uncommon within this grouping. Despite this high degree of diversity, forage grasses in general possess certain common characteristics which make such a grouping worth while for purposes of this discussion.

In the first place, all have the morphological characteristics of the grass family. In particular, their leaves are of special interest since leaves are the plant part most likely to show hunger signs. They have fibrous root systems which are quite effective in extracting water and certain nutrients from soils. Unlike a somewhat parallel group, the forage legumes, they have no built-in nitrogen supply and are completely dependent upon the soil for this vital element.

Secondly, except for the quick-growing summer annuals such as millet, Sudangrass and annual ryegrass, forage grasses grow over a relatively long season. This results in a fairly uniform demand for nutrients, spread over a period of several months, with no very pronounced peaks. Large amounts of nutrients in readily available form are not required, but adequate levels of all the essential elements must be maintained throughout the entire growing season. This calls, at times, for a different approach to fertilizer application from that followed with many

*W. W. Woodhouse is Professor of Soil Science, North Carolina State College of Agriculture and Engineering.

crops. For example, fertilizers added after establishment may be of equal or greater importance than those applied at planting, and supplies of some nutrients may have to be replenished at rather frequent intervals. Also, fertilizer applied one year may have a major effect on the next year's production.

A third common denominator is that of usage. The forage grasses are grown primarily for their above-ground vegetative parts, this vegetative growth usually being used in the feeding of animals. Continued removal of most of the above-ground growth means that the potential drain on the fertility of the land, through the removal of nutrients, by the productive species is high; thus, the likelihood of one or more elements becoming deficient, on all but the most fertile soils, is very good indeed. In other words, as a group, forage grasses may be expected to suffer from nutrient deficiencies quite often.

Deficiencies of many of the essential elements occur and have been identified on various forage grasses. Unfortunately, from a diagnostic point of view, the small, narrow leaves of these plants do not lend themselves to the development of clear-cut, distinctive, readily recognizable symptoms like those often seen on the large, broad leaves of such plants as tobacco or even on the larger leaved members of the grass family such as corn. Consequently, "deciphering deficiency symptoms on most forage grasses necessitates the reading of very fine print." The principles controlling the expression of hunger signs for various elements in corn apply in general to all the forage grasses, but due to the small size of the latter, symptoms that theoretically should appear as leaf striping, chlorosis of leaf margins, or scorching of midribs may tend to come out looking very much alike. Consequently, supplementary information, such as is obtained by soil and plant analyses, and thorough knowledge of the entire environment of the plant, often is necessary in order to properly interpret what can be seen. When dealing with nutritional problems in forage grasses, more than for most crop plants, growers should as far as possible be in position to anticipate deficiencies before having to identify them.

Enough is known about many of the forage grasses to make the anticipation and identification of at least the most common nutrient shortages feasible.

FACTORS AFFECTING NUTRIENT SUPPLY

NUTRIENT REMOVAL

One helpful bit of background information is an appreciation of the nutrients removed annually in good crops of these grasses (33). A few

examples may be shown as follows:

Species	Nitrogen N	Phosphorus P_2O_5	Potassium K_2O	Calcium CaO	Dry Matter
	pounds per acre per year				
Smooth bromegrass	108	39	171	36	6,000
Kentucky bluegrass	80	36	82	25	4,000
Coastal Bermudagrass	126	41	104	63	9,000

As these figures indicate, nutrient removal by a forage grass can be quite large, far in excess of that contained in the harvested portions of many high yielding crops grown for grain, fruit, or fiber. Obviously, the continued production of high yields of forage grasses can become quite a drain on the nutrient supply of many soils.

Attention should be called to the fact that these nutrients are removed *in toto* when forage is harvested as hay or silage and fed elsewhere. Even under grazing, with certain exceptions, removal of nutrients is, in effect, almost equally complete. Consideration of nutrient removal under grazing often is complicated by the realization that a sizeable proportion of the nutrients consumed on the pasture pass through animals and are returned to the soil in excreta. However, studies of this process indicate that under most conditions this redistribution of nutrients by the grazing animal is highly inefficient and this form of return is quite ineffective in maintaining the fertility level of the pasture as a whole (18). Exceptions occur with very high animal stocking rates, under certain soil and climatic conditions, and with elements such as phosphorus which are very immobile once they enter the soil.

SOILS

Forage grasses on the whole tend to be concentrated on the less desirable lands in any given region. These usually are occupied by soils that are not the most useful for crop production because of drainage, texture, stoniness, depth, slope, erosion, natural fertility, or other factors. These lands often are inherently lower in nutrients than the better soils of the region. Furthermore, this condition often is aggravated by their having received less than average amounts of fertilizers and lime. To be sure many exceptions occur, the more common one being where forages are grown on the better soils in rotation with other crops. Forage grasses are quite effective in utilizing residual nutrients from fertilizers applied to preceding crops. Consequently, where they are grown on good soils in rotation with well fertilized crops, deficiency problems usually are held to a minimum.

Although use of the better soils for growing forage often is justified, nothing is necessarily wrong with growing forage grasses on the less desirable soils of a farm or a region. This often represents sound land use. The ability of grass plants to utilize soils with various inherent cropping limitations is one of the strong points favoring growth of forages. However, the fact that forage grasses often wind up on the poor soils almost guarantees that these plants will be subject to their full quota of deficiencies. Such soils often are unable to supply sufficient quantities of one or more nutrients for sustained forage production. The nature of the soil usually indicates the most probable limiting nutrients. Examples may be found in succeeding sections on individual elements. The characteristics of the soil on which a forage grass is growing should be given careful study when attempts are made to anticipate or identify deficiencies.

COMPANION PLANTS

The common practice of growing forage grasses in association with other plants, principally legumes, influences the occurrence of nutrient deficiencies in the grasses in several ways. Since grasses usually are more adept at extracting certain elements from the soil than legumes, the latter sometimes can be used as indicator plants. The elements potassium (K), sulfur (S), manganese (Mn), molybdenum (Mo) and boron (B) seem to fall in this category. This means that marked deficiency symptoms of these nutrients are not likely to appear on a grass stand until its accompanying legume essentially has been starved out. Consequently, the productivity of the grass as well as of the mixture may be greatly reduced before any visual indication of the cause can be found on the grass.

Somewhat the reverse of the foregoing relationship appears to be true in the case of at least two elements, calcium (Ca) and magnesium (Mg). Grasses often are poorer competitors for these elements (6) than legumes and theoretically at least may be the first to suffer. However, different grasses seem to vary widely in their requirements for these two elements. For example, Kentucky bluegrass, smooth brome, and orchardgrass usually do best on soils that either are well limed or of limestone origin, while Bermudagrass, carpetgrass, and redtop are less sensitive to calcium (Ca) and magnesium (Mg) supplies. Also, except for those in the so-called "acid tolerant" group, legumes generally are more sensitive than grasses to "lime" factors, other than calcium (Ca) and magnesium (Mg) supplies, such as soil reaction. Consequently,

legumes often disappear before grass components of forage crops exhibit symptoms of deficiency.

Unexpected and unexplained shifts in populations within forage mixtures call for re-examination of fertilizer practices and nutrient status. These shifts may be due to cutting or grazing management, insect or disease damage, or to weather conditions. Quite often they are indicative of the development of nutrient shortages. While plants grown in mixtures compete with one another for moisture, light, and space, they also compete for nutrient supply. In soils not adequately supplied with these elements, this kind of competition often is the factor which determines which species survive. Unfortunately, the most palatable and nutritious species usually have the highest nutrient requirements and are most likely to lose out when nutrient deficiencies develop.

NITROGEN (N) DEFICIENCY

Nitrogen is essential for photosynthesis, growth, and reproduction in plants. As a major constituent of proteins and of the chlorophyl of green plants, this element is vital in the production of forage. It is important not only in influencing yield but also quality, since protein often is a rough measure of feed quality. Nitrogen is utilized in relatively large amounts by forage grasses (see listing). With the exception of some highly organic soils formed under poor drainage, principally peat and muck, most soils of the humid regions are low in this element. This is due to the rapid decomposition of organic materials and subsequent leaching of nitrogen from these soils. Most of the nitrogen applied in fertilizers is, or soon is, converted to nitrate or ammonia. Both of these forms are readily soluble, ammonia being held loosely by the soil and nitrate remaining largely in the soil solution where it is highly vulnerable to leaching. Furthermore, in warm, well aerated soils, ammonia soon is converted to nitrate and may be washed away.

Forage grasses frequently are grown in association with legumes. Where legumes make up a significant part of forage crop mixtures and have properly functioning root nodules, the grasses are able to obtain considerable quantities of nitrogen from the legumes (4). In such mixtures the quantities of nitrogen available to the grasses will be something less than the amounts that could be utilized to advantage. This is particularly true early in the year of establishment of mixtures, during which period relatively little legume nitrogen becomes available to the grass. However, attempts to supplement the nitrogen supply by fertilizing the grass growing in such mixtures beyond the seedling

stage are not generally feasible. This is due to the fact that additions of nitrogen are likely to upset the competitive balance between the grass and legume components, coupled with the tendency of legumes to utilize applied nitrogen, with a corresponding reduction in nitrogen fixation by root nodules. This substitution of fertilizer nitrogen for the fixed nitrogen within the legume nodules, reduces the efficiency of nitrogen applications and makes them of questionable value (34). Consequently, in practice, grasses, grown in mixtures with legumes, are largely dependent upon the legumes for nitrogen. Under ideal conditions, this supply will be ample for the mixture. Under conditions less favorable for legume growth and nitrogen fixation, the amount of this nutrient available to the grass may be less than optimum.

However, large acreages of forage grasses are grown in pure stands, without legumes. This practice is increasing in many areas for a number of reasons, a major one being that production of much higher yields of forage often is possible through the use of pure stands of the better grasses, heavily fertilized with nitrogen, than with grass-legume mixtures.

Where grasses are grown without legumes in humid regions, nitrogen supply usually is the first factor limiting growth. Few of these soils can supply, unaided, the amounts of this element needed for even moderately good growth of these plants. Some degree of nitrogen deficiency probably is far more widespread in grasses grown for forage than is generally realized. For example, nitrogen response has been noted in recent years on some dry rangelands, where formerly moisture had been considered the primary limiting factor (26, 27).

The degree of such deficiencies may, however, vary over an extremely wide range in the more productive species or varieties. For example, Coastal Bermudagrass can be maintained in a healthy condition by annual applications of less than 100 pounds of actual N per acre. Yet this plant may continue to show pronounced yield responses to applications as high as 800 pounds or more of actual N per acre per year (3). Obviously, in this case, anything less than 800 pounds of N is limiting growth, yet between the 100- and 800-pound rates visible differences will be confined largely to amounts of growth and to shades of green. In other words, nitrogen deficiencies of considerable economic significance may occur which in grasses are not distinguishable visually from any one of several other factors which result in slow growth and lighter than normal green color. Therefore, in practice, ability to anticipate impending shortages of this nutrient in grasslands well ahead of the development of characteristic symptoms is highly desirable.

Certain aspects of the behavior of nitrogen in soils and in grasses often make deficiencies of this element in forages fairly predictable. Nitrogen is utilized quite rapidly by these plants during periods of active growth. For this reason, a single application of fertilizer supplying this nutrient usually is effective over a relatively short period of time, one and one-half to three months. Furthermore, carry-over of applied nitrogen from one season to another tends to be quite small. Nitrogen applied prior to dormant periods, in fall or spring, but not fully utilized before growth ceases, seems to disappear from the system and not be available for use when growth resumes. Consequently, on most soils the nitrogen supply for productive forage grasses must be replenished during periods of active growth every two to three months; otherwise, nitrogen deficiency will develop.

In excessively wet seasons or under poor drainage, nitrogen losses increase or nitrogen uptake is hampered, and needs for nitrogen applications increase.

SYMPTOMS

Lack of adequate nitrogen in forage grasses is expressed in the same general manner as described for corn (Chapter II). Since this element is mobile in the plant, older leaves may be drained of it in favor of younger leaves or growing points, causing the deficiency to appear first on the older leaves. The typical symptom on the individual leaf starts as a pale green to yellowish color, followed by a "firing" of the *leaf tip*, which spreads up the midrib and later to the leaf margins (plates 1, 2, and 3). This pattern is relatively easy to see in species having larger leaves provided the plants are allowed to approach a fairly mature stage of growth before being grazed or harvested. Unfortunately, from the diagnostic point of view, the majority of grasses used for forage have rather small, narrow leaves which exhibit less distinct symptoms. Furthermore, even with the larger species, good management usually requires that the forage of established stands be utilized well ahead of the stage at which acute nitrogen deficiency symptoms appear.

Nitrogen deficiency in forage grasses can be corrected rather quickly provided moisture and temperature conditions are favorable for growth. Response to applied fertilizer nitrogen is almost instantaneous under these circumstances.

PHOSPHORUS (P) DEFICIENCY

Phosphorus is required in substantial quantities by productive forage grasses (see listing), the total amount in the harvested portion usually

being about one-third that of nitrogen. This element takes part in a large number of vital processes in both plant and animal growth. The effect on an animal suffering from phosphorus deficiency in its feed or forage is shown in figure 3, Chapter I. In plants it is a key nutrient in growth and cell division and tends to be concentrated in the young, actively growing tissues. Since these tissues usually are the most palatable and nutritious portions of the plants, production of high quality forage is quite dependent upon adequate supplies of this element.

Figure 1. Normal (left) and phosphorus-deficient (right) orchardgrass seedlings growing on Hyde loam. Note slender stunted growth of phosphorus-deficient plants in contrast to stocky vigorous appearance of normal seedlings.

Phosphorus is initially deficient in the majority of soils, and the percentage recovery of that applied in fertilizers is much lower than for nitrogen (15). It is likely to be deficient in any soil, except those formed from parent materials high in phosphorus, unless the level of this element has been built up by the continued use of phosphatic fertilizers. Phosphorus supplies are more likely to be limiting to the plant growth in the more acid soils, since this element forms very slowly soluble compounds with iron and aluminum under acid conditions. Availability of phosphorus in soils usually is highest between pH 6.5 and 7 (17).

Moisture conditions also affect the uptake of phosphorus. It is less available in dry soils, making the deficiency more likely to occur under drought or near-drought conditions.

Evidence on the relative ability of forage grasses to extract slowly available phosphorus from soils is rather conflicting. Research has shown, for example, that red clover is able to absorb more phosphorus (P) from soils treated with rock phosphate than grasses growing with it. Seedling grasses may respond to applied phosphorus more than seedling

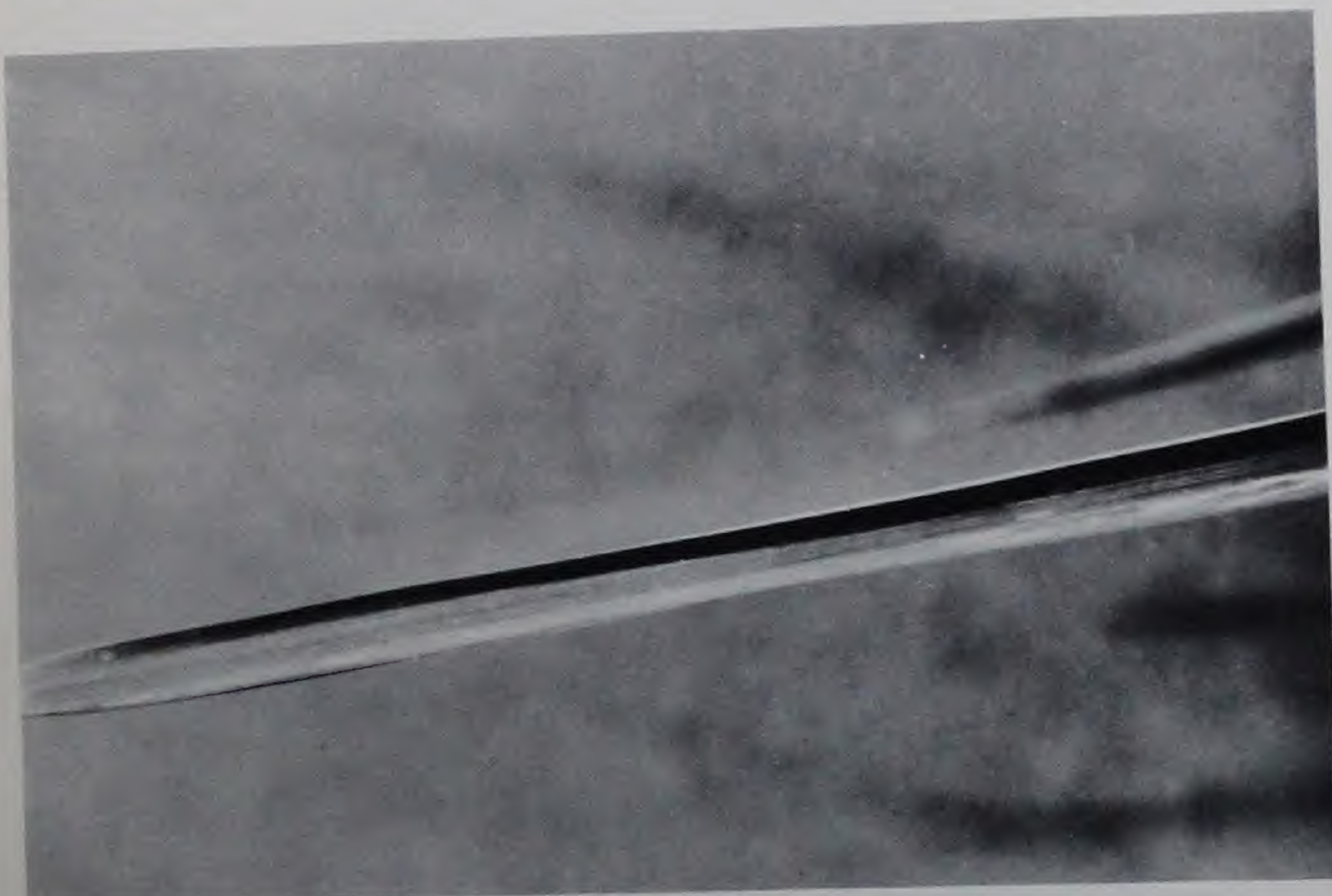


Figure 2. Leaf blade of tall fescue showing pronounced cupping and necrotic spots associated with phosphorus deficiency on established plants of some grasses.

legumes (22). On the other hand, established stands of grasses are, in many instances, able to obtain their requirements for this element from soils rather low in available phosphorus, even to the point of crowding out some legumes. This process doubtless is facilitated by having the need spread out over a long growing season. This type of demand may be met quite adequately by a slow but continuous transfer of phosphorus (P) from soil to plant. The extension of the very fibrous root systems of these plants through the soil mass also may promote this type of absorption.

Specific forage grasses vary considerably in their abilities to obtain this element from soils and to tolerate low levels of available phosphorus. Certain species long have been considered to be indicators of low phosphorus soils (20). These are for the most part undesirable grasses, such as poverty grass and broom sedge, while the better forage grasses are not well adapted to soils containing meager supplies of this nutrient. Therefore, phosphorus usually is an integral part of sound fertilizer programs aimed at the production of forage.

SYMPTOMS

Seedlings: Phosphorus deficiency is more common in seedling forage grasses than in established stands. This is probably due to both their restricted root systems and the limited amounts of this element stored in the small seeds of these plants. The young seedling is quite dependent upon fertilizer phosphorus, particularly during its early stages of development. For this reason, striking responses to applied phosphorus often are seen during this period, which may disappear completely after root systems become fully developed and are able to exploit larger volumes of

Figure 3. Leaf blade of normal tall fescue showing flat, rather than cupped, appearance of full-grown leaf.

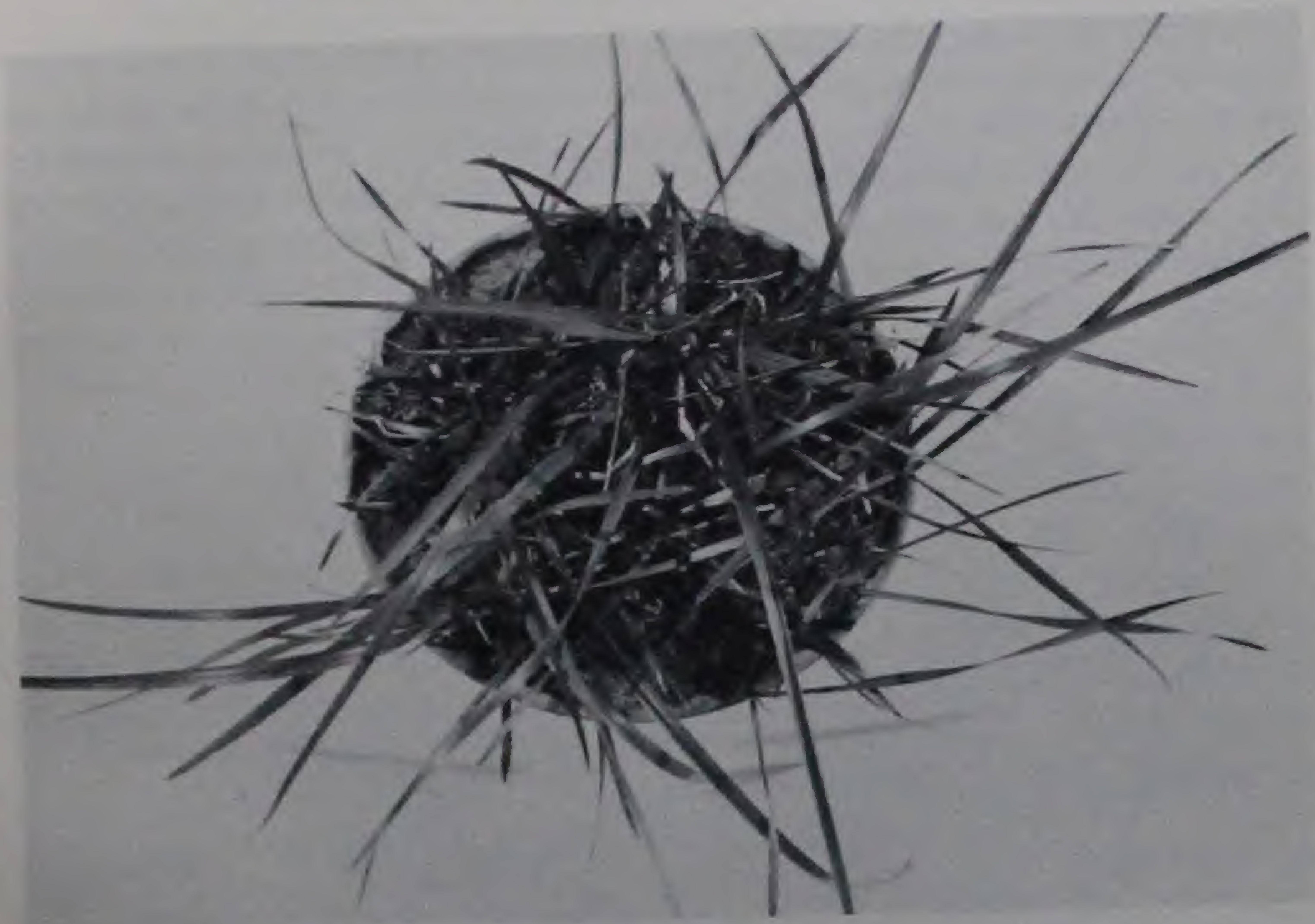


Figure 4. Tall fescue exhibiting sparse stand and coarse appearance under acute phosphorus deficiency.

soil. One should remember, however, that in spite of the often temporary character of such a deficiency it can have very undesirable effects. Since most forage grasses are grown in broadcast stands, any reduction in vigor of seedlings may hamper the development of thick, weed-free sods.

Symptoms of phosphorus deficiency in young plants are variable and not always easily identified. This is not surprising in light of the fact that this element is involved in so many plant processes and the exact expression of a deficiency of it may be expected to vary with light, temperature, rate of growth, level of other elements present and other factors.

One pattern which develops in some species, particularly in cool weather, is that of slow growth, accompanied by the appearance of an abnormally dark green color, while stems and lower leaves acquire a reddish or purplish cast. The seedling shown in plate 7 is fairly typical of this pattern. Other species, especially under higher temperatures, have an appearance of nitrogen deficiency. This suggests in such instances that the plants in reality are suffering from an internal nitrogen deficiency, since a shortage of phosphorus interferes with the assimilation of nitrates.

Established Stands: Clear-cut phosphorus deficiency symptoms are not

so readily found in well-established grass stands as they are in new plantings for at least two reasons: (1) Symptoms often are obscured by invasion of weeds or other more tolerant grasses, and (2) acute deficiencies are less frequent because older grass plants are better able to cope with low levels of available phosphorus. Furthermore, where grasses are inadequately fertilized, phosphorus deficiency often is overshadowed by nitrogen deficiency. The following description is of phosphorus de-

Figure 5. Normal tall fescue sod showing thicker stand, more vigorous growth, with leaves somewhat less coarse than in figure 4.

ficiency uncomplicated by shortages of other nutrients, a condition that may not be found very often in the field:

The general appearance of a perennial grass sod suffering from an inadequate supply of phosphorus often is that of an open, thin stand, provided, of course, that other species have not taken over and filled in the empty spaces. This may be accompanied by an enlargement of individual plants and leaves as seen in figure 4 which apparently takes place following periods of dormancy during which the very slow process of extraction of phosphorus from the low soil supply continues. Presumably, this permits accumulation of sufficient, though very small, amounts of this element to allow for the enlargement of the few remaining plants

which have been released from other factors of competition by the thinning of the stand. The net result is a thin stand of rather coarse plants. It should be borne in mind that stands having this general appearance may develop from other causes. Thinning brought about by disease also may result in sparse stands made up of rather coarse plants. Therefore, diagnosis, based solely on this factor, should be approached with caution.

Some phosphorus-deficient grasses develop a more specific symptom which, when coupled with the appearance described in the preceding paragraph, helps considerably in identifying the cause. This is the same general symptom described for seedlings. However, on more mature plants, all leaves will have a uniformly dark green color, which tends to turn purple for some distance back from the tips of the older leaves (2). When viewed in full sunlight the undersides of all leaves may exhibit a rather uniform purplish tinge. Again this seems to be primarily a cool weather phenomenon, showing up in fall or early spring, and it may be replaced in midsummer by symptoms that have more the appearance of nitrogen deficiency.

In some phosphorus deficient grasses—those with leaf blades that are normally flat, such as tall fescue, as opposed to the V shaped blades of orchard grass—the blade margins tend to curl upward, regardless of whether the front or the back of the leaf is turned up. An example of this type of symptom is shown in figure 2. This results in a decided cupping or rolling of the blade, extending through the greater part of its length and giving a boat-prow shape to the blade tip.

Recovery of forage grasses from phosphorus deficiency, following application of this element is likely to be much slower than when nitrogen or potassium is lacking and the supply is increased. In fact, where a phosphorus addition is made on the surface of a perennial sod during a dry season, improvement may not be noticeable until the following year.

POTASSIUM (K) DEFICIENCY

This element is of major importance in the production of forages, often being taken up by grasses in amounts roughly equal to or in excess of their nitrogen consumption (see listing). The role of potassium in plants is less well defined than that of some other nutrients, but it is known to be vital to several physiological functions, such as formation and movement within the plant of sugars and starch, synthesis of proteins, normal cell division and growth. From the standpoint of forage, an important effect of potassium is that of increasing the resistance of plants to some

diseases, particularly those that affect leaves and stems. Also, a deficiency of potassium may interfere with the transport of foods, such as sugars and starch, from plant tops to roots. Weak, starved root systems are characteristic of plants deficient in this element, a condition which frequently results in pronounced susceptibility to drought.

Potassium also is heavily involved in the development of resistance to cold injury in plants. This probably is a direct effect through control of the contents of the individual plant cells, and indirectly through the promotion of vigorous, more extensive root systems.

Potassium usually is not as deficient in soils initially, as is phosphorus, but potassium tends to become a major limiting factor as cropping continues. Soils are likely to be higher in this nutrient in the drier and cooler climates, and lower in the warmer and wetter regions. Most soils, with the exception of acid sandy and highly organic types, contain relatively large amounts of total potassium. Usually, only a small fraction of this total is available to plants during any one season; but, in nearly all soils, as the readily available supply is utilized, it is gradually replenished from less available forms. Most soils, through this mechanism, can furnish appreciable amounts of this element to plants year after year from their native supplies. This ability varies widely among soils and often is referred to as their "potassium supplying power." Potassium deficiency will develop on any soil, even though it may contain large quantities of total potassium, if the rate of removal by crops exceeds its "potassium supplying power."

Many plants will take up amounts of certain elements far in excess of their actual needs. This is called "luxury consumption," an activity to which potassium is particularly vulnerable and a habit to which forage grasses often are addicted. This phenomenon has several practical implications in the maintenance of adequate fertility levels under sods. It makes any build-up of reserve supplies of available potassium in such soils particularly difficult. Consequently, annual additions of this nutrient are needed in most situations where the requirements of the crop exceed the potassium supplying power of the soil. Large, infrequent applications, such as are often made with phosphorus on permanent type sods, are not likely to be very efficient in case of potassium.

Another closely related and equally important factor is the ability of most forage grasses to extract potassium from the soil much more readily than can legumes growing with them (1). This results, at times, in a legume-grass mixture in which the legume is suffering from acute potassium deficiency while the grass component still is at a luxury consump-

tion rate of intake of this nutrient. Maintaining levels of potassium high enough for the legume without unduly encouraging excess consumption by the grass can be difficult with grass legume mixtures. This problem is, however, the basis for one very useful rule, namely, "in legume-grass mixtures, take care of the potassium needs of the legume and the grass will fend for itself."

Perennial forage plants, legumes as well as grasses, require rather continuous supplies of potassium over a long growing period. Consequently, available potassium may be high at the beginning of the season under productive sods but become depleted to a dangerously low level before growth ends. In such situations, with legume-grass mixtures, clovers usually run out of potassium, are crowded out by the still healthy and vigorous grasses, and disappear so quickly that no distinctive symptoms can be seen on them. At the same time, grass growth may even be temporarily accelerated by the release of nitrogen from the dying clover. Yet by the end of the season, the grasses also may be suffering from lack of potassium.

Shortages of potassium are much more likely to start limiting growth of forage grasses after the growing season has been under way for a while than at the beginning. This is due to at least two factors: (1) Demands for this nutrient on the part of these plants are relatively steady throughout the season. That is to say, potassium needs during any one month are roughly proportional to growth during that month. Consequently, the supplies at the beginning of spring growth often are adequate for one or two months but become overdrawn after that time. This is likely to occur on any soil with a low "supplying power." Monthly withdrawal from "available" simply exceeds monthly deposits from "unavailable" until the former is exhausted. (2) This phenomenon is coupled with release to available forms of potassium fixed in clays, or in primary or secondary minerals, that takes place over winter to some extent in most soils. Roots of perennial forages apparently are able to pick up some of this released potassium prior to initiation of above-ground growth. This pre-growth accumulation is believed to help explain the relative scarcity of potassium hunger signs or of pronounced depression of growth due to insufficient levels of this element in these plants at the beginning of the growing season.

One rather glaring exception to the foregoing rule occurs under cold, wet conditions. Potassium uptake is greatly hampered in cold, water-logged soils and, under these conditions, rather acute potassium deficiency

symptoms may develop in early spring on soils that are able to support normal growth after they warm up.

SYMPTOMS

Potassium moves readily in plants so that the younger leaves and growing points usually draw this nutrient from the older leaves whenever a shortage occurs. In the larger forage grasses, such as millet, symptoms follow the same general pattern as described for other large-leaved members of the grass family, such as corn. Good examples of this may be seen in plates 6 and 13. Initially, growth slows down and older leaves take on a yellowish streaked appearance, followed by scorching or firing of leaf tips and margins. This is in contrast to nitrogen starvation in which damage progresses from leaf tips up the midribs, and leaf margins retain their green color for a while.

In the smaller-leaved members of this group, potassium deficiency develops much less distinct patterns as shown in plates 9, 11, and 12. Under some conditions, thinning of stands may be the first outward manifestation of the difficulty. Indications are that thinning often comes about as a result of the direct action of disease organisms on plants that have become weak and susceptible through potassium starvation. It often is accompanied by a speckled, diseased appearance of the remaining plants resulting from severe infestations by leaf and stem pathogens. In fact, excessive damage from leaf diseases probably is the most common symptom of this deficiency to be found on the fine-leaved forage grasses.

Although thinning from shortage of potassuim results in sparse stands, the appearance of remaining plants will be different from those in sods weakened by lack of phosphorus. As pointed out earlier, plants surviving phosphorus deficiency may actually develop larger, coarser appearing leaves than plants in dense, healthy stands. Potassium starved plants, on the other hand, are likely to remain stunted with short narrow leaves as in figure 6, and, in the case of bunch type grasses, in small compact bunches.

Susceptibility to drought is another symptom to watch for when a potassium shortage is suspected in the fine-leaved grasses. Sods that are deficient often have the appearance of suffering from severe drought during midday when moisture supplies are ample for normal plants in adjacent areas.

In practice, keep in mind that inadequate levels of available potassium often result in significant reductions in growth of forage grasses without development of distinctive hunger signs. The range between

maximum growth and acute deficiency is not nearly so wide as that indicated for nitrogen. It is large enough, however, to be of considerable practical importance. Therefore, knowledge of the soil and the plant involved, soil and plant analyses, and all other available aids should be utilized in anticipating potassium deficiencies before they reach the symptom stage.

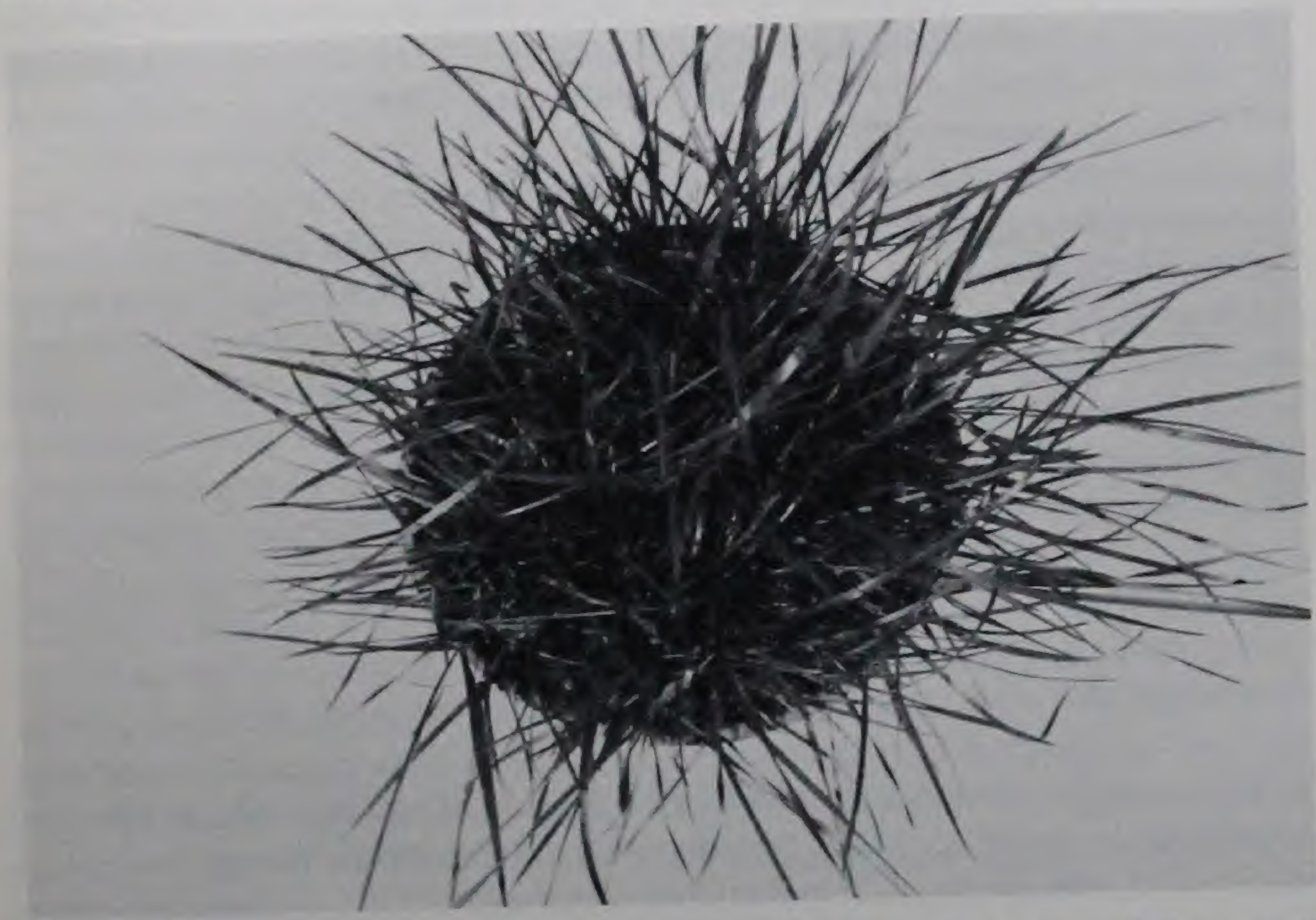


Figure 6. Potassium-deficient tall fescue showing finer leaves than those of the normal plants in figure 5. Attention is called to the fact that this photo was made after new growth was initiated in the greenhouse. This gives the stand a more dense appearance than actually existed in the field.

Unlike in most annual crops, appearance in perennial grasses of signs of potassium starvation does not necessarily indicate that remedial measures will fail. Potassium application at this late stage often is very worthwhile provided the stand itself has not been too badly depleted.

MAGNESIUM (Mg) DEFICIENCY

Magnesium is a part of the chlorophyl molecule and as such is essential to the green color in plants. A shortage of this element will show up in the older leaves since it moves readily from the older to the younger tissues. Magnesium is required by plants in smaller amounts than

is nitrogen (N) or potassium (K), but in much larger quantities than the so-called "trace elements." Magnesium together with calcium (Ca) and sulfur (S) are often referred to as "secondary elements." This term refers to the relative amounts of these elements required for normal plant growth. They are not of secondary importance, being just as essential to the growth of plants as any other element. Magnesium tends to be low in acid soils, and lowest in sandy acid soils. This element is added to soils along with calcium in dolomitic limestone or in magnesium salts in fertilizer; it usually is lost from soils, through leaching, more rapidly than calcium.

The magnesium contents of some forage grasses tend to be quite low in comparison with those of legumes growing in association with them. Although magnesium deficiency has not been identified very frequently in these grasses in the past, this element has been receiving more attention in recent years. For one reason, a very serious nutritional disturbance in cattle and sheep sometimes occurs, called grass tetany or hypomagnesaemia, which is rather generally believed to involve an imbalance in the ratio potassium to the total amount of calcium plus magnesium $\left(\frac{K}{Ca + Mg}\right)$ in some forages. Some indications have been found that grass tetany can be prevented by the application of magnesium to pastures. Although this difficulty seems to occur under several different sets of circumstances, one of the more critical conditions appears on highly fertilized, grass-dominant sods. Concern about grass tetany has focused considerable attention upon the magnesium contents of forages, and has resulted in the finding of rather low amounts of this element in many soils (32).

The incidence of magnesium deficiency probably will increase in certain areas as the use of grass dominant or pure grass stands, liberally fertilized with nitrogen, becomes more general. More plentiful supplies of nitrogen fertilizers and more efficient varieties of grass are making this practice increasingly attractive. At least two factors in this system will increase the pressure on soil magnesium unless they are taken into account: (1) High yields of forage will remove considerable quantities of this element, and will necessitate more frequent additions on soils low in magnesium. (2) Since most sources of fertilizer nitrogen are acid forming, use of higher rates of nitrogen (N) will lower soil reactions (pH) and tend to accelerate depletion of supplies of magnesium. Consequently, steps should be taken to guard against magnesium deficiency, particularly where large yields of forage grasses are produced on acid, sandy soils, as

with Coastal Bermuda in the southeastern states. Strong suspicions are developing that magnesium deficiency affecting livestock health may occur on many acid soils.

SYMPTOMS

Magnesium deficiency in the larger-leaved grasses starts with a stunting and yellowing of the older leaves. As this symptom progresses, a definite striping effect occurs. Green or yellowish green stripes alternating with yellow to whitish stripes run the full length of the leaves.

In the smaller leaved grasses, this striped effect is less pronounced or entirely missing. Instead, whole leaves bleach to pale yellow or almost white. In sod forming grasses this occurs first as irregular patches or streaks of stunted grass with varying amounts of leaves showing the bleaching. Thinning of stands in and around these patches soon is apparent. An example of this in a fine-leaved, sod-forming grass is shown in plate 14. Winter injury is aggravated by magnesium deficiency. Weak spots or streaks in sods of species that are subject to this type of damage may develop over winter and loss of chlorophyll from some of the remaining plant leaves may show up the following summer (35).

Application of corrective measures on magnesium deficient forage grasses after symptoms appear often is worthwhile. This is particularly true of sod forming grasses since they fill in weak spots readily when properly treated. Ordinarily, dolomitic limestone is used to supply magnesium to forages but where deficiency symptoms already have developed, faster acting soluble magnesium salts usually are a desirable supplement.

CALCIUM (Ca) DEFICIENCY

Calcium, an essential part of cell walls, is involved in the translocation of foods within plants, affects the availability of other nutrients, acts as a neutralizing agent on toxic substances formed within plants, and plays numerous other less well understood roles (19). In forage grasses, it is, of course, important to the nutrition of animals consuming the plants. This element is taken up by forage grasses in considerable quantities (see listing) and "lime response" in some cases probably is due in part to the supplying of calcium as a nutrient. However, this element is added to soils in limestone, superphosphate, and in some other fertilizer materials. Consequently, in most soils it apparently is present in sufficient quantities to prevent development of recognizable deficiency symptoms before the effects of other deficiencies or unhealthy conditions such as

low soil pH come into play. Probably for this reason, calcium deficiency under field conditions has not been reported on forage grasses.

Though less sensitive than most legumes, grass plants respond to applications of liming materials. In such instances, no clear-cut symptoms appear. Prior to liming, the grasses may be lighter green in color than usual and growth may be somewhat retarded (2). Perhaps this condition should be termed "lime deficiency" rather than "calcium deficiency." Correction of this symptom by application of limestone may involve any or all of the several direct and indirect effects attributable to liming.

SULFUR (S) DEFICIENCY

Sulfur, as a constituent of certain proteins, is a vital element in the growth of forage grasses. Well-drained soils contain sulfur primarily in organic matter. They receive additions of this nutrient through sulfur-containing fertilizers, decomposition of plant materials, and from sulfur-bearing gases in the atmosphere brought down in rain or snow. The amounts contributed in precipitation vary widely, from as much as 100 pounds per acre per year in some heavily populated industrial regions to less than 5 pounds in some sparsely settled areas.

Sulfur is not "built up" to any extent in most well drained soils except as organic matter is accumulated. Consequently, low organic matter soils usually do not retain very much of this element very long, even though they may have received large quantities in the past from such materials as superphosphate. However, appreciable amounts of sulfur may accumulate as sulfate in the acid subsoils of some of the soils of the southeastern states, but the sulfate in this case is held much less firmly than phosphate (12, 13).

Sulfur is required by forage grasses in fairly small amounts relative to nitrogen, roughly 10 to 1 (30). Sulfur deficiency has not been identified in these plants very frequently in the past. However, under some situations sulfur has become extremely limiting to the growth of forage grasses (14, 21). These conditions are found in areas where soils are low in organic matter, little sulfur has been added in fertilizer materials, and only limited amounts are brought down in precipitation. One or more of these conditions seem to apply in fairly large areas in the Pacific Northwest, parts of South America, and probably many other places. As the trend to higher analysis fertilizers continues, with less of this nutrient applied incidental to fertilization, more widespread occurrence of sulfur deficiency may be expected. As long as they can obtain sufficient nitrogen, forage grasses apparently can take up sulfur almost to

the total exclusion of clovers growing in association with them. Where this element is in limited supply, the grasses in a clover-grass mixture may monopolize sulfur, as it becomes available, to the extent that nitrogen fixation in the clover nodules declines or ceases altogether (30). In such situations the productivity of the mixture will then be directly limited by nitrogen supply and only indirectly by lack of sulfur. Probably some degree of sulfur deficiency is far more widespread in forage grasses than is generally realized.

SYMPTOMS

The milder forms of sulfur deficiency in forage grasses are difficult if not impossible to identify visually. A check for growth response to sulfur application is the easiest and surest procedure where a shortage of this element is suspected. Where sulfur is limiting, application of this nutrient usually will bring about improvements in grass color and growth within a few weeks.

Sulfur deficiency has been identified on several forage grasses growing in pure stands (14, 35). Initially the leaves become pale green, a symptom usually not distinguishable from the early stages of nitrogen deficiency. As the condition becomes more acute, however, affected plants develop a pattern quite different from those suffering from nitrogen shortage. Apparently, some movement of this element occurs from older to younger tissues but this usually is slower than with nitrogen. The result is that young leaves are often more severely affected and may become chlorotic before older leaves, as shown in plate 15 and to a lesser degree in plate 16. The older leaves tend to remain alive for a time, rather than to rapidly wither away as in nitrogen deficiency.

A deficiency of this nutrient can be corrected rather quickly by application of any of several materials containing sulfur. Calcium sulfate, elemental sulfur, and sulfur bearing sources of nitrogen, phosphorus, and potassium are the ones in most general use. Applied sulfur gradually is lost from soils through leaching. Where conditions conducive to sulfur deficiency in forage grasses exist, applications of this element are likely to be needed from time to time.

COPPER (Cu) DEFICIENCY

Copper functions in plant growth as an enzyme activator, or as a part of certain enzymes, and is important in the utilization of proteins.

Although the mechanisms involved are not well understood, copper is strongly held in soils. Availability of this element to plants is affected

by soil reaction; it is least available in a pH range of 7 to 8 and increases in availability as the soil becomes more acid. Quantity of organic matter and kind and amount of clay minerals present in a soil materially affect its copper availability. Copper frequently is found to be deficient in plants grown on peat and muck, soils high in organic matter.

Acute deficiencies of this element have been reported in forage grasses in the Florida Everglades (7). Pangola, St. Augustine, and annual ryegrass, all three, responded to copper additions. Pangola was quite sensitive to low levels of copper and was replaced within a few months on untreated areas by common Bermudagrass. St. Augustine was much more tolerant, as was paragrass. Bermuda, St. Augustine, and paragrasses were found to be capable of producing acceptable growth at copper levels so low as to produce copper deficiency in animals consuming them. Annual ryegrass was more susceptible than St. Augustine, but more tolerant than oats (8). Apparently, oats and wheat would be good indicator crops in anticipating copper deficiency in forage grasses.

SYMPTOMS

This element apparently is quite immobile within the plant and therefore is not redistributed from older to younger tissues. Consequently, the younger leaf tips and growing points are the first affected. In grasses, entire plants become stunted and yellow in color, followed by necrosis (dying) of growing points and the tips of the younger leaves (see plate 17).

Reports of copper deficiency in forage grasses appear to be confined to soils high in organic matter. However, responses to this nutrient have been made by other members of the grass family, such as small grains, (36) grown on mineral soils, low in organic matter. This suggests that copper responses may be expected to turn up eventually in forage grasses on other soils.

Copper deficiency may be corrected by the application of any of several materials containing this nutrient, copper sulfate being the one most often used. Copper in excessive amounts is toxic, and caution should be exercised in applying it to soils. Copper additions to soils usually produce strong residual effects and copper toxicity can be more troublesome than copper deficiency.

Since movement of copper in many soils is very restricted, disked-in treatments may be more desirable than surface applications in preparation for growing perennial grasses.

MANGANESE (Mn) DEFICIENCY

Manganese is involved with iron in the synthesis of chlorophyll and in the maintenance of proper distribution of iron within plants. Manganese deficient plants often contain deposits of insoluble iron compounds in their conductive tissues. Manganese exists in soils in a number of different forms, the particular form being heavily influenced by soil reaction. Manganese solubility is favored by acid soils having pH below 6, and the element tends to shift to insoluble forms as the pH rises above this point. The less acid soils tend to retain larger amounts of this element with little of it in available form. The more acid soils, on the other hand, are likely to be low in total manganese due to leaching of soluble forms. Most soils are able, however, to maintain a rather low but adequate supply of this element in a form available to plants. However, when the pH of a strongly acid soil is raised above 6 by liming, or of an organic soil by burning, manganese deficiency is likely to occur. The small amount of this element present is rendered insoluble by the sharp rise in pH. The most frequent occurrence of manganese deficiency is on soils of this kind that have been "overlimed."

SYMPTOMS

Manganese deficiency in perennial ryegrass, annual ryegrass, orchardgrass, and timothy has been described by Walsh (31). Symptoms include chlorosis of the younger leaves, with yellow-green spots on the older leaves and withering of leaf tips. Gray specks of dead tissue appear between leaf veins, merging lengthwise to form bands parallel to the veins. Later these bands may join across the leaf resulting in withering and downward bending of the tip portion.

Manganese deficiency has not been widely identified on forage grasses. However, indications are that some species and strains may be susceptible as the oat plant. Since "gray speck disease," as manganese deficiency is called in oats, is not extremely unusual, low levels of this element probably limit the growth of some forage grasses more often than is presently realized.

ZINC (Zn) DEFICIENCY

Zinc is essential in the formation of growth-promoting and growth-regulating compounds in plants. Consequently, a deficiency of this element results in structural abnormalities within them. Continued enlargement rather than division may result in oversize, oddly shaped cells, with many air spaces among them, in various plant parts.

Deficiencies of zinc occur in plants growing in a very wide range of soils. This is because the deficiency results from a low total amount of zinc in some soils, but more often of low availability of the soil zinc. Most soils actually contain ample quantities of this element, which may or may not be available due to any of a rather wide variety of reasons.

Zinc availability is affected by soil reaction, being highest at the lower pH values, low in the range between 5.5 and 7.0, and somewhat unpredictable above pH 7.0. Zinc availability may be depressed by high soil phosphorus, addition of liming materials, presence of free lime in the soil, and by a number of other soil conditions. The ability to bind zinc in unavailable form is so strong in some soils that deficiencies in plants grown on them are best corrected by direct application of zinc sprays (24).

SYMPTOMS

Forage grasses in general do not appear to be very sensitive to levels of soil zinc. However, zinc hunger signs are fairly common in some members of the grass family. "White bud" in corn is due to lack of this element and its occurrence has been reported on acid mineral soils in a number of areas.

Sudan grass, an annual forage plant, appears to have somewhat the same susceptibility to zinc deficiency as corn. Quite probably, a deficiency of this element will be found to limit growth of other forage grasses. This is most likely to occur in areas where other, more sensitive crops, have exhibited zinc hunger.

Symptoms in the larger leaved grasses, such as Sudan, develop with the appearance of light yellow streaks between the veins of the older leaves (29) sometimes accompanied by reddening of leaf sheaths and blades (25). White spots may appear on the leaves and some small areas may never develop chlorophyl. Young bud leaves may become practically white in extreme cases.

Zinc deficiency may be corrected by applications of soluble zinc salts, such as zinc sulfate. Zinc chelates are used on soils with high zinc-fixing capacities, or foliar sprays containing zinc sulfate may be applied. Chelates are complex organic compounds with metal ions attached, from which the metal is readily available to plants.

MOLYBDENUM (Mo) DEFICIENCY

Molybdenum is of particular interest in forage production on two counts: (1) It is essential in the nitrogen fixing process in legumes, where

it is utilized in extremely small quantities. (2) Even quite low concentrations of this element in forages are dangerous to livestock. As little as 10 ppm (on a dry weight basis) is considered to be the borderline concentration for the development of molybdenosis or Teart disease in cattle or sheep. According to some indications, under certain conditions a subclinical level of molybdenosis may be induced by concentrations in forage as low as 5 ppm; yet, plants may contain as high as 100 ppm without obvious outward change in appearance (28).

In addition to being essential to the nitrogen fixing process in legumes, this element is required in the nitrogen metabolism of all plants.

Molybdenum deficiency has been described by Hewett (9) in perennial ryegrass, velvetgrass, and orchardgrass. However, grasses in general are much more adept at satisfying their requirements for this element from soils low in molybdenum than are legumes and most other broad leaved plants (11). Therefore, probably deficiencies of this element seldom occur in grasses under field conditions.

Symptoms described are development of pale yellow foliage similar to nitrogen deficiency followed by extensive bleaching and withering of leaves. Molybdenum naturally is in very low supply in some soils, particularly those derived from serpentine rocks. Most soils are well supplied with this element, but the more acid types may be deficient in available molybdenum due to fixation in unavailable forms. In many of these soils, liming will release adequate quantities of this nutrient. Where necessary to supply molybdenum salts to forage crops, rates of application should be kept quite low—ounces rather than pounds per acre—and treatments should be repeated at infrequent intervals (5).

BORON (B) DEFICIENCY

Boron apparently is involved in a multitude of plant processes including cell division, flowering and fruiting, carbohydrate and nitrogen metabolism, and water relations. The amount of boron in most soils is quite small and its availability is influenced by a number of factors. Boron occurs in soils in both organic and inorganic forms. It is firmly held by clays, and hardly at all by sands. Fixation usually increases with rising soil pH, but deficiencies of this element are most widespread in humid regions where soils generally are acid. Dry weather in some way interferes with boron uptake, causing deficiency in plants to be much more prevalent under drought conditions.

Plants are extremely variable both in boron requirements and in boron uptake. Alfalfa, for example, has a very high requirement for this element

while grasses in general require fairly low amounts (23). Boron deficiency has been reported in one member of the grass family, corn (16), but apparently it seldom if ever occurs in forage grasses under field conditions. It not infrequently affects these plants indirectly through associated legumes.

Boron is quite immobile in plants, a characteristic which causes deficiency symptoms to develop first in the younger leaves and at growing points. Boron deficiency usually results in plants with shortened internodes in their upper parts and some form of chlorosis in their younger leaves.

Boron should be applied to soils with caution since this element accumulates in clay subsoils and can be extremely toxic to plants.

IRON (Fe) DEFICIENCY

Iron is an essential element in the growth of plants. It is involved with manganese in the formation of chlorophyll, and a deficiency of this element usually is reflected in a decrease in the chlorophyll of leafy plant growth. This results in a lighter color of the inter-veinal areas of the younger leaves, which change to yellow as the deficiency advances.

Iron deficiency occurs in plants grown on calcareous or heavily limed soils, where it is called "lime-induced chlorosis" and also in plants grown on acid soils, particularly those which prefer acid conditions. Iron is difficult to supply in a form available to plants in soils where a deficiency exists. Consequently, application of this nutrient directly to plants in sprays often has been necessary. More recently iron chelates are coming into use (10).

Fortunately, at present, forage grasses very rarely appear to suffer from iron deficiency.

GUIDE TO THE OCCURRENCE OF NUTRIENT DEFICIENCIES IN THE FORAGE GRASSES

Due to the wide variability encompassed, this group of plants does not lend itself very well to a nutrient deficiency symptom key. The following tabulation, intended as a general guide to the probable occurrence of the respective deficiencies may be found helpful:

	Nitrogen N	Phosphorus P	Potassium K	Magnesium Mg	Calcium Ca	Sulfur S	Copper Cu	Zinc Zn	Manganese Mn	Molybdenum Mo	Boron B	Iron Fe
Frequency of occurrence in forage grasses:												
Often	X	X	X									
Occasional				X		X						
Rare							X	X	X			
Very Rare					X					X	X	X
Frequency of occurrence in grasses versus legumes:												
More often	X											
Less		X	X	X	X							
Much Less						X			X	X	X	
Frequency of occurrence under varying moisture supply:												
Dry weather		X									X	
Cold-wet weather	X		X									X
Frequency of occurrence on foliage of varying maturity:												
Younger leaves					X	X	X		X		X	X
Older leaves	X	X	X	X				X				
Frequency of occurrence under varying soil conditions:												
Acid	X	X	X	X	X	X				X		
Alkaline							X	X			X	X
Sandy	X		X	X		X		X				
Low organic matter	X					X						
High organic matter							X	X				
Limed									X			X

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Plate 1. Early stages of nitrogen deficiency in young pearl millet. Note firing of older leaves and pale green color of young leaves.

Courtesy of N. C. Agricultural Experiment Station

Plate 2. Acute nitrogen deficiency in pearl millet. Plants in center received no fertilizer nitrogen while plot to left received 100 pounds of nitrogen per acre 3 weeks prior to photo.

Courtesy of N. C. Agricultural Experiment Station

Plate 3. Nitrogen deficiency in established Coastal Bermudagrass. Note thin, pale green to yellowish sod in the center, in contrast to dark green and rank growth of nitrogen fertilized plot to the left.

Courtesy of E. H. Bailey, American Potash Institute

Plate 4. Phosphorus deficiency on Johnson grass. Note red to purple coloration of older leaves and slender fragile appearance of the plant.

Courtesy of N. C. Agricultural Experiment Station

Plate 5. Phosphorus deficiency on first year plants of Coastal Bermudagrass. The two dark green plants with very short stolons (left) are phosphorus-deficient. The lighter green vigorous stolons creeping over from the right are from plants with adequate phosphorus.

Plate 6. Potassium deficiency on pearl millet. Note firing of tips and margins of older leaves, areas along the midribs remaining green. Youngest leaf next to head has normal green color.

Courtesy of E. H. Bailey, American Potash Institute

Plate 7. Phosphorus-deficient orchardgrass seedling, approximately twice actual size. Note reddening of sheath of lower leaves, firing of upper portion of oldest leaf, darker green color and stunted appearance when compared with normal seedling in plate 8.

Courtesy of N. C. Agricultural Experiment Station

Plate 8. Normal orchardgrass seedling.

Courtesy of C. S. Brown, University of Maine

Plate 9. Potash-deficient timothy. The 50 pounds of K_2O applied to this plot annually was inadequate under high nitrogen fertilization, 300 pounds N per acre per year. The phosphorus supply was adequate. Note diseased "rusty" appearance and stunted growth in comparison to normal timothy in plate 10.

Courtesy of C. S. Brown, University of Maine

Plate 10. Normal timothy. Received same nitrogen and phosphorus application as plot in plate 9, but three times as much potassium.

Courtesy of Jose Vicente-Chandler, ARS, Puerto Rico

Plate 11. Guineagrass. Potassium-deficient plot in foreground, healthy plants in background. Note firing or rusting of older leaves of deficient plants.

Courtesy of N. C. Agricultural Experiment Station

Plate 12. Potassium deficiency in Coastal Bermudagrass. Note browning of lower leaves and generally weak, rusty appearance of the sod.

Plate 13. Potassium-deficient Johnson grass. Note firing of tips and margins of leaves with areas along mid-rib remaining green.

Courtesy of E. H. Bailey, American Potash Institute

Plate 14. Magnesium deficiency in established Coastal Bermudagrass. Note extreme chlorosis and dwarfing in a spot near the center of the picture, surrounded by a larger area of stunted, thin growth.

Courtesy of N. C. Agricultural Experiment Station

Courtesy of J. K. Spencer, C.S.I.R.O. Canberra, Australia

Plate 15. Sulfur-deficient Hardinggrass (left) and normal (right). Note that most of the leaves of the deficient plants are chlorotic, with little difference between younger and older leaves.

Courtesy of IBEC Research Institute

Plate 16. Sulfur deficiency in Bahiagrass. Dark green plot received nitrogen plus sodium sulfate while surrounding area received nitrogen only. Photo made two weeks after treatment.

Courtesy of W. T. Forsee, Jr., Florida Agricultural Experiment Station

Plate 17. Copper-deficient Pangolagrass. Note sparse growth, slow spreading, and slight chlorosis of plants growing on this highly organic soil. Typical of many copper-deficient areas. These plants died out completely in a few months.

Courtesy of W. T. Forsee, Jr., Florida Agricultural Experiment Station

Plate 18. Pangolagrass receiving 50 pounds per acre of copper sulfate. Note darker green color and greatly increased vigor in contrast to untreated plot above.

Courtesy of D. E. Baker, Pennsylvania Agricultural Experiment Station

Plate 19. Magnesium deficiency symptoms on orchardgrass. Top left—adequate magnesium supply (plant content 0.30% dry wt.); center—adequate magnesium followed by period of no magnesium (plant content 0.04% of dry wt.); right—plant grown continuously at low level (plant content 0.03% of dry wt.). Bottom left—Leaves from normal and deficient plants. Bottom right—Portions of leaf blades from magnesium-deficient plant (left), and normal plant (right).

Chapter VII

Nutrient Deficiencies in the Potato

By G. V. C. Houghland *

THE WHITE or Irish potato is adapted to a wide range of soil and climatic conditions. In the United States it thrives from Maine to the lower Rio Grande Valley of Texas, and from the Atlantic to the Pacific coast (figure 1). Important commercial-producing districts, presenting a wide variety of growth conditions, are located at high and low altitudes and in humid and semi-arid regions. In these districts crops are grown with different lengths of daylight, under sunlight of different qualities and intensities, and on soils that vary widely in texture and in natural fertility. To each environmental influence the potato plant responds in a somewhat different manner. Deficiency symptoms due to the lack of one or more than one element are not always the same under all conditions, but certain abnormalities seem to be characteristic, and these will be given consideration.

The needs of the potato for different nutrient elements are about the same as those of other crop plants, but this does not necessarily imply that the potato requires a given element in the same quantity or at the same time as other plants. The potato may not have as big a need for certain elements as other crops. For example, some crops, including celery, cauliflower, turnips, and sugar beets, appear to be much more susceptible to boron deficiency than is the potato.

Conjectures often are made about the soil conditions responsible for nutrient deficiencies, but the forces at work are apt to be so insidious that the critical stage of a crop disturbance may not manifest itself definitely for some time. For example, when magnesium deficiency began to develop in a number of important potato-producing sections along the Atlantic Seaboard, the supply of available magnesium in the soil was almost exhausted before definite symptoms of magnesium deficiency

* G. V. C. Houghland is plant physiologist, Crops Research Division, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland. The original chapter on this subject, and that in the 1949 edition, were prepared jointly by H. A. Jones, Head Horticulturist, and B. E. Brown, Senior Biochemist in the U.S. Department of Agriculture, in conjunction with the present author.

were generally observed. The continued use of certain fertilizers tended to increase soil acidity, and the trouble spread rapidly. After considerable experimental work, the remedy was found to be the addition of magnesium compounds with the fertilizer mixture or directly to the soil. Combining magnesium compounds with the fertilizer mixture gave a quicker effect and insured a supply of magnesium for the young potato plants.

The writer has been unable to find a single case reported in the United States of a deficiency of boron, calcium, or copper which has affected the potato when grown in the field. However, salts containing these elements have been applied to potato soils in this country with results differing from little to no response, and in a few cases actually causing depressions in growth and yield (3, 11, 12, 13, 15, 16, 21, 22, 24, 25, 26, 29).* Manganese deficiency has been reported in naturally calcareous or overlimed soils because under such conditions this element is made comparatively unavailable for use by plants (10). Other elements—boron and zinc—are reported to be affected similarly by an excess of calcium carbonate (23). Potato soils in the East, however, are generally acid in reaction, and perhaps this is why boron, copper, and zinc deficiencies are not problems. For the same reason iron and manganese present no problems. In the more detailed discussion to follow, no reference has been made to aluminum, molybdenum, and a number of other so-called minor elements because no evidence at the present time indicates that they are deficient in potato soils. The time may come, however, when an element not now established as essential may turn out to be a vital factor in potato production.

When the plants are grown under controlled conditions in sand and solution cultures, descriptions of deficiency symptoms observed by various investigators are in much better agreement. These artificially produced symptoms help to point the way to a finer differentiation of deficiency symptoms when they occur under field conditions.

NITROGEN (N) DEFICIENCY

A deficiency of available nitrogen is a distinctly limiting factor in the growth of the potato plant—perhaps more generally so than a deficiency of any other essential element. Some source of nitrogen—manure, commercial fertilizer, green-manure crops, or a combination of these—is almost always utilized in commercial potato production, except possibly on organic soils, such as muck and peat.

* Refers to references listed at end of this chapter.

Figure 1. Healthy potato vines free from any nutrient deficiency (top). Healthy foliage and growth. Splendid yields are the result of careful culture and plant feeding. Potato vines responsible for such a yield as this received a well-balanced diet with no deficiency of any nutrient element (bottom).

In Virginia an acre of potato plants during the first 50 days after planting utilized less than 7 pounds of nitrogen as measured in the growth above ground, during the next 10-day period absorption of nitrogen averaged 1 pound a day, and during the next 20-day period it averaged 2 pounds a day. After about the eightieth day, when growth above ground had practically stopped, a gradual transfer of nitrogen from the foilage to the developing tubers occurred (6).

The reaction of the potato to nitrogen deficiency is similar to that of many other crops. The growth of the entire plant is restricted in accordance with the extent of the deficiency (plate 1), and this stunted condition is reflected in reduced yields and poor quality tubers. The plant takes on a light-green to yellowish-green color. In advanced stages, the

margins of the lower leaflets lose their chlorophyll, the color fading to a pale yellow (plate 1, lower right), and shedding of some foliage usually results.

Nitrogen deficiency usually is associated with sandy soils that are low in organic matter and acid enough to restrict growth of the bacteria responsible for nitrification. A fertilizer practice that fails to offset nitrogen losses from the soil, as a rule, ultimately results in acute nitrogen deficiency. Preventive measures include liming to control soil reaction, adding organic matter in the form of manure, composts and green manures, and using commercial fertilizer at the proper time and rate to provide an ample supply of available nitrogen.

PHOSPHORUS (P) DEFICIENCY

Phosphorus absorption rates during the growing season correspond closely to those of nitrogen, but the greatest amount of phosphorus absorbed is about one-sixth that of nitrogen in Virginia (6) and one-twelfth that of nitrogen in Maine (14). At the time the plants reach full growth, 50 to 75 percent or more of the phosphorus in the tops has been conducted to the developing tubers (6, 14, 18). A supply of phosphorus which is inadequate generally causes pronounced growth reactions (plate 3). The plants are smaller than normal, somewhat spindling, and definitely retarded in growth—particularly terminal growth—during the early stage of development.

Potato plants grown on phophorus deficient soil may produce tubers with rusty-brown lesions in the flesh in the form of isolated flecks. Sometimes they are joined together to produce larger discolored areas forming radial patterns—streaks running out from a center. Usually no external distinction develops between normal and affected tubers, but when the latter are boiled, the flecks remain hard brown masses in the softened tissue. Brown flecks in the flesh of potato tubers may be due to other causes besides phosphorus deficiency; for example, they may be caused by a virus disease, or heat or frost injury.

When potato plants are grown in sand or solution cultures with solutions deficient in phosphorus (plate 2), the leafstalks (petioles), leaflets and their margins turn upward. The leaflets are smaller and darker than normal, and the plants are somewhat rigid (17, 18, 28).

Phosphorus deficiency occurs on a wide range of soil types—on heavy soils because of fixation, which makes the phosphorus unavailable; on light soils because of naturally low phosphorus content; and on both types because of crop removal. Lack of available phosphorus may be re-

flected more in low yields and poor quality than in distinctive foilage symptoms, but the latter will develop where continuous cropping is practiced without adequate phosphorus applications.

POTASSIUM (K) DEFICIENCY

The potato plant must have a continuous supply of potassium for normal growth. Where a deficiency exists growth of the plant is first

Courtesy of Crops Research Division, Agri. Res. Serv., U. S. Dept. of Agri.

Figure 2. Potato plant grown in solution culture without potash. The leaves show marked symptoms of potassium deficiency.

retarded and finally completely checked; the internodes are somewhat shortened, which gives the plant a compact appearance.

The leaves are reduced in size, due to a narrow arrangement of the leaflets, which form sharper angles with leaf petioles and become crinkled and curve downward.

Early appearance of abnormally dark green foliage is one of the most dependable signs of potassium hunger. Then the older leaves become yellowish, and a brown or bronze color develops, starting from tips and edges and gradually affecting entire leaves, which finally die (plate 4, top). In a single plant this bronzing is not so striking, but it is quite

prominent in mass effect. Under certain light conditions a distinct purplish cast is apparent. A number of the lower leaves may dry up at the same time, leaving a tuft of dark-green leaves at the apex, or top, of the plant. Eventually, the entire plant dies (figure 3).

Sand cultures also have been used in studying potassium deficiency symptoms of the potato, and the responses reported are similar to those described for plants growing in the field (28). The leaves, leaflets, and leaflet margins bend downward. The color of the leaves changes from

Figure 3. During World War I potash became scarce. Rows on left received 5-10-0 at rate of 1 ton per acre; rows on right, 4-8-4 at the same rate. Much earlier collapse of plants where no potash was in the mixture is very evident.

a normal healthy green to a dark green and afterwards to a peculiar bronze or yellow, beginning with the oldest leaves. Symptoms on the lower leaves may be pronounced while the tops of the plants still have a normal appearance (figure 2). The diseased tissue of the leaves protrudes strongly between the veins. In severe cases the leaf margins break down, and discolored areas appear on various parts of the stems and petioles. The tuber stolons are shorter than normal and the roots and tubers are poorly developed.

Yields decrease proportionally as the shortage of potassium increases. In the United States the area most generally affected is that lying east

of the Appalachian Mountains, particularly the sandy soils of the Atlantic Coast States. Deficiency symptoms have been noted as far north as Aroostook County, Maine, being more prominent there on Washburn than on Caribou soil. In general, deficiency occurs on light sandy soils of a leachy nature and mucks and peats. Some heavy soils high in total potassium, however, are too low in available potassium to satisfy the needs of a potato crop, which requires from 100 to 200 pounds of potash per acre. During World War I, when supplies of potash fertilizer became very low, deficiencies became serious (figure 3).

Fortunately, quantities of potassium salts in this country at present are sufficient to remove any fear of serious crop reduction from potash hunger.

Obviously, the remedy for potassium deficiency as it affects the potato is to utilize any available manure or fertilizer containing sufficient available potassium.

MAGNESIUM (Mg) DEFICIENCY

Magnesium deficiency symptoms on potatoes have been reported from practically all of the potato districts of the Atlantic Coastal Plain and as far north as Aroostook County, Maine.

The foliage of affected plants is lighter in color than it should be. The lower leaves are the first to become affected, since some of the magnesium is withdrawn to be used by new growth. In mild cases, only the lower leaves of the plants show symptoms, while the new growth appears healthy. Loss of green color begins at the tips and margins of the lowermost leaves and progresses between the veins toward the centers of the leaflets. In advanced stages of deficiency the central portions of the individual leaflets become chlorotic between the veins and eventually are filled with small brown dead areas. Breakdown of tissue, like loss of color, usually starts at the tips of the leaves, and terminal leaflets generally are the ones most severely affected. The lower leaves of magnesium deficient plants are brittle, which serves to distinguish them from leaves yellowing naturally through age.

In a severe case nearly the entire leaf area is affected and all of the plant, except the terminal growth, is involved. Such plants have a very marked chlorotic and stunted appearance and some of their lower leaves roll upward. Their leaflets become thick and brittle and show a definite bulging between the veins. These symptoms seem to be more conspicuous after a warm, dry spell when the potato plants are 8 to 10 inches tall. Finally, the chlorotic leaves die, turn brown, and often drop off (plate 5).

In Holland, when the potato variety, President, was grown under controlled conditions in glass sand in the absence of magnesium, the symptoms were more severe but similar to those observed in the field (28). Chlorosis developed at the tips of the lowermost leaves, then advanced along the margins and between the veins until the entire leaf was involved. The terminal leaflet was attacked first, then the other leaflets. Chlorosis progressed from the lowermost leaves upward, and in severe cases the chlorotic tissue was almost pure white and protruded upward, while the tips and margins of the diseased leaflets bent downward. Growth of roots and tubers also was checked. In the presence of excess nitrogen, symptoms were still more severe.

Magnesium deficiency in potatoes is associated with a combination of very low magnesium, rather low calcium, and relatively high nitrogen content in the lower leaves. In normal aging, the lower leaves have a high content of magnesium and calcium but are low in nitrogen (6). Investigations in Virginia have shown that symptoms of magnesium deficiency do not appear in plants containing over 0.4 percent of magnesium oxide; but, under conditions of excessive rainfall during the early months of the growing season, coupled with the heavy use of acid-forming fertilizer, magnesium is liable to become a limiting factor on even the most fertile types of potato soil (7).

Results of experiments in Aroostook County, Maine, have shown that the so-called "potato sickness" prevalent in that district and specifically associated with magnesium deficiency may be effectively controlled by applying a magnesium compound to the soil. Substantial increases in yields of Green Mountains and Irish Cobblers were obtained by incorporating magnesium sulfate at rates equivalent to 30 pounds of magnesium oxide (MgO) per acre with ordinary potato fertilizer (8, 9), or in spray mixtures (2), particularly in fields where severe chlorosis developed shortly after the emergence of the plants. Deficient plants sprayed with magnesium bordeaux showed recovery in new growth, lived longer, and yielded more. In one test, the yield from the use of magnesium bordeaux was 96 bushels per acre more than the yield in adjacent plots sprayed with high-calcium bordeaux. On less deficient soil in the same field, the yield was increased only 38 bushels per acre. In another test, the magnesium bordeaux increased yields 133 percent on deficient soil and 11 percent on better soil. These results suggest that some of the spray stimulation reported in the past may have been due to absorption of magnesium by the plants from magnesium lime in the bordeaux mixtures used.

Magnesium deficiency generally occurs in highly acid soils, but it is not necessarily confined to those that are light and sandy, for its effects have been observed on soils of high fertility, such as Caribou loam in Aroostook County. Heavy applications of acid-forming fertilizers, particularly those containing certain nitrogenous materials have increased the solubility of the magnesium compounds, which subsequently were leached away from the feeding range of the young potato plants.

Practical remedies for magnesium deficiency consist of light applications of dolomitic limestone made directly to the soil; introduction of magnesium sulfate, generally a calcined form, into the fertilizer mixture, at a rate to furnish 30 to 40 pounds of magnesium oxide per ton; addition of enough dolomitic limestone to the fertilizer mixture to make it neutral; or a combination of two or more of these measures (20). Foliage sprays of magnesium bordeaux, or of a 2 to 3 percent solution of magnesium sulfate, are quick-acting remedies, but soil applications produce more lasting effects.

CALCIUM (Ca) DEFICIENCY

Though only about one-fourth as much calcium as potassium is used by the potato plant, calcium plays an important part in the plant's development besides creating a favorable soil environment for growth (6). Calcium has an indirect effect on the growth of the plant by altering the availability of certain nutrients and preventing the toxic effects of others.

Potatoes grow well in acid soils at pH values between 4.8 and 5.5. When the soil is more acid than this, unfavorable conditions develop, such as aluminum toxicity and phosphate fixation. Soils less acid may prove favorable for the growth of the scab organism; though yields may not be reduced, scabby tubers are undesirable for market and whole crops even may be valueless.

The intake of calcium into the aerial portion of the potato plant is continuous, and the amount present reaches its peak at maturity. Very little appears to be removed from the older portions of the plant to the developing buds and shoots, and for this reason a continuous supply of available calcium from the soil to the growing regions is necessary if deficiencies are not to occur. Also, transfer of calcium from aerial portions to developing tubers seems to be negligible (19). Studies in Virginia show that only about 7 percent of all the calcium absorbed by the plant is located in the tubers.

One might expect to find calcium deficiency symptoms in potatoes in regions where acid soils and heavy rainfall prevail. However, such symp-

toms have not been reported, therefore reference to calcium deficiency symptoms induced artificially is necessary (plate 6).

Deficiency symptoms on potato plants grown in sand culture with limited calcium are characteristic and pronounced (28). First, a light-green band appears along the margins of the young leaves of the terminal bud. The tissue in these light-colored areas may be killed; consequently, the leaves do not develop normally and often have a wrinkled appearance. In severe cases the young leaves at the top of the plant remain folded and later the tip dies. The axillary growth which develops later may show the same symptoms as did the young leaves of the terminal bud.

In the medullary or pith regions of the tubers, dead spots develop; these areas show first as diffuse brown discolorations within the vascular ring at the stem end of the tubers. These symptoms may show up in tubers from plants that had healthy looking foliage, an indication that when calcium becomes deficient late in the life of the plant the effect is primarily on the tuber, there being very little or no transfer of calcium from the aerial portions of the plant to the tubers to take care of the deficiency. Thus, a continuous supply of calcium must be available as long as new organs are being formed and new tissues are being developed.

Calcium deficiency usually develops later in the growth of the plant than magnesium deficiency owing to differences in solubility and leaching of the respective compounds. Potatoes growing on light sandy soils, which are more nearly devoid of calcium compounds than heavier soils, generally suffer first. Obvious remedies are to prevent excessive acidity by the use of limestone and by incorporation of suitable calcium compounds with the fertilizer mixture when these are known to be lacking in the materials used.

BORON (B) DEFICIENCY

Boron deficiency symptoms of potatoes have been reported from time to time. In the field they have been described as occuring chiefly in tubers rather than on vines. Only minute quantities of boron are needed for normal growth, and few reports of vine injury under field conditions due to the lack of this element have been published. Where a deficiency of boron exists, field applications have given noticeable growth responses, such as hastening the emergence of plants and bringing them into bloom 10 to 14 days before those without boron applications.

A report of field experiments by the New York (Cornell) Agricul-

tural Experiment Station indicates that boiled potato tubers grown without boron addition to the soil showed much sloughing (falling away of the outer layer), were fairly soggy, and possessed a flat flavor definitely inferior to that of tubers grown with added boron. The effects of adding 20 pounds of borax per acre were to produce a material reduction in sloughing, an increase in mealiness and dryness, and an improvement in texture, flavor, and color (27). However, the quality of dehydrated by applications of 7½ pounds of borax per acre contained in ferti-
potatoes, including their color and flavor, was reported to be unaffected
lizer (5).

During World War I and for a time afterward, considerable injury occurred to the potato crop from excess amounts of borax in fertilizers. Subsequent experiments have shown, however, that the bad effects on yield may have been due largely to the manner in which the borax was applied. On Caribou loam in Aroostook County, Maine, definite injury occurred when 5 pounds per acre were applied in the furrow directly before planting. Surplus borax may prevent sprouting of seed pieces and thereby produce poor stands. Other effects are killing of the sprouts after some growth has occurred, failure of roots to form, weak appearance of those plants that finally emerge, bleaching of the foliage or marginal yellowing of the leaves, and abnormally low yields (4).

A number of investigators in both Europe and America have developed solution and sand culture procedures for growing plants with insufficient boron. Special precautions against boron contamination have been found necessary because only a minute amount of this element is needed for normal functioning of the plant (plate 7).

Typical boron deficiency symptoms of potato plants include: Growing points die, and tips of terminal shoots are stimulated into a characteristic growth of lateral buds. Internodes remain short and give the plant a bushy appearance. Leaves thicken and margins roll upward, a symptom similar to that of potato leaf roll virus. When the boron deficiency is not great, only a slight upward curling of the margins of the older leaves is visible. With greater deficiency, petioles become brittle, loss of green color (chlorosis) appears, and in severe cases anthocyanin (a purple pigment) is developed. The leaf points and margins, especially those of the older leaves, die prematurely. Starch congestion in leaf tissues is conspicuous.

In an advanced stage of boron deficiency, potato roots are short, thick, and have a brown appearance. Root tips die, and this stimulates the development of secondary rootlets which in turn may die soon after emergence (figure 4).

Internal symptoms of boron deficiency are first found at the growing points of the roots and afterwards at the growing point of the stem. These symptoms appear as a brown discoloration resulting from a breakdown of individual cells or cell complexes before the growing point is killed. Later, the stem, the axillary buds, and the internal parts of the lateral shoots become diseased; next the tissue of the nodes is attacked, that of the highest first, then that of the internodes.

From the work of Ora Smith and L. B. Nash

Figure 4. Lack of sufficient boron seriously interferes with the root development of the potato plant. Fibrous roots are seen to be very much restricted in growth.

Boron deficient tubers are smaller than normal and often have ruptured surfaces. The green portion of the plant may be markedly diseased, whereas the tissue within the tubers may show slight symptoms or none at all. Again, the tubers may develop typical symptoms, such as a local brown discoloration below the skin, generally at the stem end of the tuber, or a brown discoloration of the vascular ring—most pronounced at the stem end but varying in the distance it extends toward the apex—or both.

Although boron deficiency has not as yet become a problem of potato growers in this country, nevertheless under certain conditions a light

broadcast application, 10 to 15 pounds per acre, of sodium borate (ordinary borax) may be beneficial. Small amounts of chemicals can be thoroughly mixed with larger amounts of sand or other inert materials for even distribution. Use of slightly moist sand prevents segregation. Soluble chemicals can be dissolved and the solution sprayed on sand or fertilizer or directly on the soil.

MANGANESE (Mn) DEFICIENCY

Manganese deficiency has been noted on certain truck soils of the Atlantic Seaboard, but no clear-cut description of how it affects the potato has been given (1, 10).

Courtesy of J. R. Neller, Florida Agricultural Experiment Station

Figure 5. When the supply of manganese is insufficient, potato plants show it; not enough manganese (above), enough manganese (below).

In solution cultures deficiency symptoms on potatoes appear as light-green chlorotic areas in the interveinal tissue of the upper leaves. Later, numerous little brown patches develop along the veins and these dead areas increase in both size and number. When lack of manganese is not severe, the upper parts of the plants become somewhat chlorotic but do not develop dead spots (plate 9).

Even on highly calcareous or heavily overlimed soils, 50 to 75 pounds of manganese sulfate per acre is likely to be sufficient to meet any

deficiency of this element. On some acid soils, an excess of manganese in the soil solution sometimes may be great enough to create a toxic condition.

SULFUR (S) DEFICIENCY

Sulfur deficiency symptoms in the potato appear to have been encountered in the United States only in nutrient culture studies (figure 6), and seem never to have been observed under field conditions. When

Courtesy of Crops Research Division, Agri. Res. Serv., U. S. Dept. of Agri.

Figure 6. This potato plant (left) exhibits pronounced sulfur deficiency symptoms. The leaves and veins are yellowish with slight upward roll, and small brown necrotic areas occur between the veins.

the mixed fertilizers used contain appreciable amounts of superphosphate, ammonium sulfate, and occasionally potassium sulfate, there is little likelihood of sulfur hunger developing in potatoes. Observations on other plants show that when a shortage of sulfur exists, leaves may become yellow, stems woody, and root development may decrease. Research shows that sulfur tends to increase root growth and may have a role in chlorophyll development. Most investigations indicate that symptoms resulting from a shortage of sulfur develop slowly.

If concentrated fertilizers are used which contain no sulfur, a deficiency on light sandy soils may develop. Obviously, the inclusion of appropriate sulfur compounds in fertilizer mixtures used in such areas is necessary.

IRON (Fe) DEFICIENCY

A deficiency of available iron results in a malnutritional chlorosis which requires treatment with an iron salt to overcome the conditions or at least to prevent further development. Like those of boron, manganese, and zinc, iron deficiency usually is found on highly calcareous or overlimed soils. This condition makes the iron less available and causes a so-called lime-induced chlorosis. On acid soils a deficiency of iron is a very remote possibility. Search of agricultural literature has failed to disclose any description of iron deficiency symptoms in relation to potato plants in the field.

In solution cultures, with iron omitted the first symptom on potatoes is a slight chlorosis in the young leaves, rather regularly spread over the blades. The points and margins of the leaflets keep their green color longest. Since both the green and yellow pigments are affected, the discolored tissue becomes a clear pale yellow, and in extreme cases almost pure white. The chlorotic tissue is curved upward. Leaves that develop before the symptom appears retain their green color.

On acid soils usually sufficient iron is available in the soil solution to take care of growth requirements. Since potato growers tend to prefer acid soils because of their inhibitory effect on the development of the scab organism, little possibility of iron deficiency occurs in the production of this crop. To correct iron deficiency in other crops, the salt most generally used is ferrous sulfate.

COPPER (Cu) DEFICIENCY

Copper now is considered by some soil scientists to be essential to plant growth, but convincing proof still is lacking as to whether it is essential or indirectly beneficial. No authentic case of copper hunger except on organic soils seems to have been recorded in the agricultural literature. Potatoes grown on mineral type soils rarely, if ever, suffer from lack of copper. This perhaps may be ascribable to the fact that copper sometimes is applied to potato plants in certain spray mixtures in sufficient amounts to prevent a deficiency. Some of the added copper gets into the soil, while some may be absorbed by the potato foliage.

Copper sulfate is the copper salt usually applied to the soil to correct a deficiency of this element.

ZINC (Zn) DEFICIENCY

Zinc now is accepted provisionally as an element essential for plant growth. Very little of this element is required by plants. Present knowl-

edge indicates that some plants either need less zinc than others or are able to obtain their needed supply more readily. Zinc deficiency symptoms on potatoes recently have been reported as developing on soils known to be deficient in this element. Affected plants are stunted, and young leaves are cupped and roll upward to the extent that terminal growth resembles that of a fern. The term "fern leaf" is used to describe this symptom of zinc deficiency in the potato. Very little of a positive nature is known about the metabolic activities of zinc; some investigators believe its action is indirect and possibly related to phosphorus nutrition.

Potato plants growing in solution cultures without zinc are reported to show distinct deficiency symptoms. Growth of the plants is slow and they never attain the size of those supplied with zinc; the top leaves assume a slightly vertical position, while the margins of some of the leaflets curl slightly upward in a manner suggesting the early symptoms of leaf roll virus. Leaves of zinc deficient plants are smaller than those of controls, their upper internodes are shorter, and their stems are more rigid.

Plants without zinc form grayish-brown to bronze irregular spots that usually appear first on leaves halfway up the plant, but sometimes on the older or on the younger leaves, and finally on almost all the leaves. The affected tissue becomes sunken and finally dies. Badly diseased plants have brownish spots on their leaf petioles and stems. Plants grown without zinc are significantly shorter than normal and are smaller in weight of foliage and tubers.

On acid soils enough zinc goes into solution to prevent the appearance of zinc-deficiency symptoms in potatoes. A deficiency possibly might occur on highly calcareous soils or on those heavily limed. To correct zinc deficiency in other crops, zinc sulfate has been used. Whenever zinc sulfate is used to activate a fungicidal spray for potatoes, a small amount of zinc always is supplied to the soil in the spray residue.

WHEN MORE THAN ONE ELEMENT IS DEFICIENT

Potato plants grown in river sand with both potassium and phosphorus omitted have normal shape and color, but the growth of stems, roots, and tubers is strongly reduced (28).

With phosphorus and nitrogen omitted, petioles, leaflets and leaf margins are more erect than in the case of phosphorus deficiency alone, and

leaves are lighter green. Such plants are dwarfed and very stiff, their leaflets are small, and their roots and tubers are poorly developed.

With potassium and nitrogen omitted, the dark-green color characteristic of potassium deficiency is absent but interveinal tissue protrudes upward and leaves and margins of leaflets are curved downward. The plants remain small and their roots and tubers are poorly developed.

Where all three of these important elements—potassium, phosphorus and nitrogen—are omitted, growth is severely limited, but the plants are close to normal in shape and color.

At present very little is known concerning the combined influence of a deficiency of two or more minor elements on the potato plant. For example, with both boron and calcium well below optimum physiological requirements, growth reactions may be expected to be a blending of the individual effects of the deficiencies of the two elements, or the symptoms of one deficiency may dominate or mask those of the other.

KEY TO NUTRIENT DEFICIENCY SYMPTOMS OF POTATOES

General characteristics: Growth reduced. Effects more or less localized. Parasitic or virus disturbances absent. Color of plants change.

Element Deficient

A. Effects on entire plants or confined to older or lower leaves.

B. General yellowing and drying up, or "firing," of lower leaves. In acute stages, reddish to purplish color develops in lower leaves.

C. Color fades, beginning with tips and margins of leaflets, until all foliage becomes light green. In time color may fade to pale yellow. In extreme cases margins of lower leaves become devoid of chlorophyll and curl, sometimes "firing." Stunted growth and defoliation are characteristic.............................Nitrogen

C. Foliage crinkly and dark green. In acute cases lower leaves become purplish. Plants remain stiffly erect. Petioles, leaflets, and leaf margins take an upward direction. Leaflets often cup-shaped. Leaves fail to expand to normal size. Growth is seriously affected when deficiency is acute. Tubers may have internal rust-brown lesions.......................................Phosphorus

B. Localized, mottling or chlorosis (loss of green color), with or without necrotic (dead) spots on lower leaves; practically no drying up of lower leaves.

C. Lower leaves lighter green than normal. Chlorosis begins at tips and margins of lowermost leaves and progresses between veins toward centers of leaflets. Eventually tissue between veins is filled with brown dead areas. Definite bulging between veins and thickening of foliage occurs. Affected leaves are brittle.....Magnesium

C. Foliage darker green than normal. Leaves reduced in size. Internodes remain short. Plants have a humped-up, recurved appearance. Foliage becomes crinkled, and veins appear sunken. Later, older leaves become a trifle yellowish. Then bronzing develops from tips and margins and gradually involves entire plants. Bronzing particularly evident in mass effect. In late stages plants susceptible to attack by parasitic organisms.....Potassium

C. Lower leaves chlorotic; others grayish-brown to bronze with irregular spots; first development usually on leaves midway of plant but eventually practically all foliage is affected. Spots become sunken and involved tissue finally dies. In extreme cases internodes remain short and leaves small and thick. Spots develop on petioles and stems, top leaves assume a slightly vertical position, and margins of leaves may curl upward to the extent that growth resembles that of a fern........Zinc

A. Effects localized on newer leaves.

B. Terminal bud dies, preceded by unusual distortions at tips or bases of the young leaves making up terminal growth.

C. Young leaves of the terminal bud lighter green than normal, the lighter color being most pronounced at the base. Stem tip may die or make distorted growth. Internodes remain shortened, giving plant a bushy appearance. Leaves become thickened and roll upward, and leafstalks brittle. Anthocyanin (purple pigment) may develop. Tips and margins, especially of lower leaflets, die prematurely. Tubers remain small and often have ruptured surfaces..Boron

Element Deficient

C. Earliest symptom is light-green band along margins of young leaflets of terminal bud. Such areas often die (necrosis), giving leaflets a crinkled or buckled appearance. In some cases young leaves at top remain folded, causing tip to die. Margains of leaflets often roll upward. Axillary buds may show same symptons as terminal bud. Tubers develop dead spots in pith region. These first show as a diffuse brown discoloration within the vascular ring at stem end.............................Calcium

B. Terminal bud remains alive; newer leaves chlorotic, with or without spots of dead tissue; veins light or dark green.

C. Young leaves show loss of turgor and remain permanently wilted. Terminal bud tends to droop when flower buds are developing, especially if shortage is marked. Drying of leaflet tips occurs in advanced stages. No pronounced chlorosis develops...........Copper

C. Slight uniform chlorosis develops in young leaves. Tips and margins maintain green pigment longest. Principal veins retain normal green color. Affected tissue gradually becomes pale yellow. Foliage becomes white in extreme cases. No dead spots in evidence..Iron

C. Leaf areas lighter green than normal, first between veins and in tops of stems. These areas may become yellow to white. Numerous small brown patches develop which in time become more extensive. Lower leaves least affected. Mild shortage causes only slight chlorosis, chiefly confined to upper part of stem, and no dead spots develop...................................Manganese

C. Symptoms develop slowly. General yellowing of leaves and veins occurs similar to that in nitrogen deficiency without leaves drying up. Growth of the plant is materially checked. Some spotting of the leaves occurs if shortage is acute or prolonged...Sulfur

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Courtesy of Va. Truck Expmt. Stn. and Crops Research Div., Agri. Research Serv., U.S. Dept. of Agri.

Plate 1. The potato plant (above left) is normal. The plant (above right) shows incipient stages of nitrogen deficiency, of which rolling of leaflets and general reduction in size and vigor are predominant symptoms. The leaf (below left) is normal. The leaf (below right) is from a potato plant growing in soil highly deficient in nitrogen. It is characterized by light-green color in the center of the leaflets and distinct loss of chlorophyll at the margins, and shows a tendency to "fire" and curl at the edges.

Courtesy of Crops Research Division, Agricultural Research Service, U.S. Dept. of Agri.

Plate 2. Potato plants showing phosphorus deficiency symptoms. Critical stage resulting from extremely low phosphorus supply (left). Terminal growth has stopped; plant did not recover when phosphorus supply was increased. Incipient stage showing stunted growth, dark green foliage, and cupping of lower leaves with some tip-burn (right). This plant recovered when phosphorus supply was increased.

Courtesy of Maine Agricultural Experiment Station

Plate 3. Normal growth of potatoes that received 2,000 pounds of 4-8-8 fertilizer (left). Potatoes showing phosphorus deficiency symptoms (right); they received the same amount of nitrogen and potash, but no phosphorus. Such plants are darker green in color, stunted in growth, their foliage is crinkly, and their leaflets fail to expand normally. Their growth continues beyond the normal time of maturity.

Courtesy of Crops Research Division, Agri. Res. Serv., U. S. Dept. of Agri.

Plate 4. Advanced stage of potassium deficiency in a potato plant (top), showing leaves bronzing and yellowing with dead edges. Magnesium deficiency in the field (bottom).

Courtesy of Va. Truck Expmt. Stn. and Crops Research Div., Agri. Research Service, U.S. Dept. of Agri.

Plate 5. Magnesium deficiency as it affects the potato. Four stages, including (1) normal leaf; (2) first symptom at tip of terminal leaflets; (3 and 4) advancing stages. Loss of color and "firing" of foliage are prominent symptoms. Foliage is characteristically brittle in advanced stages.

Courtesy of J. A. Chucka and S. M. Raleigh, Maine Agricultural Experiment Station

'late 6. Calcium deficiency (right) produces a light-green band along the margins of the oung leaves of the potato plant and causes the terminal bud to cease to function, giving a osetted effect. In serious cases the terminal bud dies and subsequent growth is from the sides. Normal plant (left).

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 7. Potato plant lacking boron (right). Leaves thicken and the margins roll upward. The main characteristic is death of the terminal bud. Some chlorosis develops, and petioles become brittle. Leaf points and margins die prematurely. Terminal growth of potato plant completely arrested by boron deficiency (left).

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 8. This potato plant (left) did not receive manganese, and the results of the deficiency are clearly shown. Light-green color developing in the inter-veinal tissue is the first symptom. Normal potato plant (right).

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 9. The final stage of manganese deficiency is shown in the potato leaf (left) which is practically devoid of chlorophyll. Normal potato leaf (right).

Chapter VIII

Nutrient Deficiencies in Vegetable Crops

By E. R. Purvis and R. L. Carolus *

MANY currently recognized symptoms of nutrient deficiencies in plants were first identified in vegetable crops. Vegetables are subjected to nutrient stresses because of their rapid growth, high nutrient requirements, and intensity of production. They mature in from 30 days (radish) to 90 days (tomato), and their market quality is more clearly related to adequate nutrition than in more slowly developing field crops. Satisfactory soil structure, assuring adequate oxygen in the rooting zone, is extremely essential for satisfactory nutrient absorption by vegetable crops.

The quantity of nutrients used by vegetable crops averages considerably higher than that of most field crops, and 75 to 80 percent of the total requirement must be available during the 60-to-90-day period of most rapid development. Growers generally accept that nitrogen should be high in fertilizers for leafy foliage crops, that phosphorus should be high for fruit crops, and potash high for root crops. This is only a generalization, however, as lettuce frequently is injured by large amounts of nitrogen in hot weather, and most determinate types of tomatoes are materially benefited by nitrogen side dressing after initial fruit is set. Cabbage and cauliflower yields frequently are reduced by a lack of adequate potash; and the market quality of sweet corn in normal seasons generally is benefited by a side dressing of nitrogen.

At the beginning of this century, use of manures and organic fertilizers maintained a fairly even supply of plant nutrients during the growth period. Because of the relatively slow release of nutrients from these materials, both injury to seedling roots and nutrient loss by leaching were reduced. In addition, these materials contained significant quantities of some of the trace elements. When these materials become economically unavailable and growers became virtually dependent on chemical fertilizers, both major and trace nutrient deficiencies became wide-

* E. R. Purvis is Professor of Soils, Rutgers University, and R. L. Carolus is Professor of Horticulture, Michigan State University. The authors of the chapter on this subject in the 1949 edition of this volume were J. J. Skinner, senior biochemist, Bureau of Plant Industry, U.S. Department of Agriculture, and Dr. Purvis.

spread. To supply the quantity of nutrients required in soluble form for the developing crop without injuring young seedling roots, fertilizer placement practices were developed which, in addition to preventing injury, reduced fixation of fertilizer-applied phosphorus.

To insure satisfactory crops, in addition to nitrogen, phosphorus and potassium, many soils in the United States must now be supplied with magnesium, boron, manganese, copper, or zinc; and, in many parts of the arid West and in certain areas in Florida, with iron. During the last 20 years, need for supplementary molybdenum, particularly on more acid soils, has been established, and calcium and sulphur deficiencies are beginning to appear where growers are dependent on high analysis fertilizers. In a few situations, benefits from chlorine have been observed where this material is not being supplied in the fertilizer.

Just as the total nutrient requirements of vegetable crops vary with the quantity removed and other factors, symptoms of malnutrition due to a deficiency are not identical in all crops or varieties, or on all soil types. Frequently, symptoms in sand or water cultures are more pronounced and somewhat different from those exhibited in the field. However, because metabolic processes associated with the development of protoplasm involve many elements, deficiency symptoms of many nutrients are remarkably similar. Some of the outstanding symptoms of deficiencies in vegetable crops that are, or might become, economically important are discussed and illustrated in this chapter.

NITROGEN (N) DEFICIENCY

Symptoms of nitrogen deficiency probably were the first signs of malnutrition in plants identified by man. Nitrogen, a constituent of both chlorophyll and protoplasm, is vitally essential to energy transformations within the plant and to the development of its cellular contents. Vegetable growers know from experience that light-green to yellow leaves, coupled with retarded growth, are indications of nitrogen starvation in their crops, and that the maintenance of a continual nitrogen supply is necessary for the production of high-quality vegetables.

Although the total nitrogen content of mineral soils varies from less than 500 to about 4000 pounds to the acre, the greater part of the element is contained in the organic fraction where it is not immediately available to plants. Therefore, on wet cold soils in early spring, nitrification frequently proceeds at such a low rate that nitrogen becomes limiting to rapidly developing vegetable crops. Since many vegetable soils are low in organic matter and of sandy texture, they contain little

nitrogen and rapidly lose it through leaching after it is oxidized to the soluble nitrate form.

Use of nitrogen fertilized green manures or winter cover crops in rotation with vegetables helps maintain nitrogen in slowly available organic form for absorption following periods of leaching rainfall. Application of a considerable percentage of the nitrogen requirements of vegetables to the proceeding green manure crop has been found by growers to be desirable, additional nitrogen being supplied as warranted by temperature and rainfall during the growing season.

Plants are able to utilize nitrogen in ammonium, nitrate, or urea forms, the nitrate forms being the most quickly available. In early stages of vegetable plant growth, due to limited root development, some available nitrogen in the rooting zone is advantageous if not too close to the seed.

The first indication of nitrogen deficiency is strikingly similar in most vegetable crops. Growth of shoots and roots are restricted. Tops are short and thin, growth is upright and spindly, and leaves are small, usually a pale yellowish-green color in the early stages of growth. Under low temperature conditions some purpling may develop in tomatoes, cabbage, and sweet corn. Lateral shoots are few while lateral buds may remain dormant or die. Frequently, fungus diseases infect the plant and spread through and deteriorate the lower foliage. In the final stages the entire plant may often change from light yellow to golden yellow and finally to a desiccated brown.

During rapid growth, the upper petioles or stems of most normal vegetable plants contain at least 800 parts per million (ppm), fresh weight, of nitrate nitrogen. As the crop matures and vegetative growth diminishes, the content of nitrate nitrogen generally drops to less than 500 ppm. However, in young, rapidly growing plants, a concentration of less than 500 ppm usually indicates a developing deficiency that should be corrected at once.

The first sign of nitrogen deficiency in tomatoes is retardation of growth followed by a change in normal green color, first noticeable in the tips of the younger leaves in the tops of the plants. These leaves remain small and thin and entire plants gradually become light green to pale yellow in color. From yellowish-green, the veins of the leaves soon turn purple, the color being accentuated on the undersides of the leaves. The stems become hard and fibrous and may take on the same deep purple color found in the veins (plate 1). Roots of nitrogen deficient tomato plants at first are more fully developed than tops, but they finally become stunted, turn brown, and die. Flower buds

turn yellow and shed; fruits are small, and yields are greatly reduced.

In cucumbers and muskmelons, early symptoms of nitrogen deficiency are exhibited in stunted leaf growth and lightening in color of foliage. The normal green of the leaves fades to several shades of green and yellow until in extreme cases all the chlorophyll is broken down. Stems are slender and become hard and fibrous. Fruits from nitrogen-deficient cucumber plants are light in color and pointed at their blossom ends; (plate 2) muskmelons are small in size. Lack of an adequate continual supply of available nitrogen in the soil is one of the principal causes of low yields of both melons and cucumbers.

Nitrogen deficiency in radishes is indicated by retarded growth, with leaves that are narrow, thin, and finally yellow. The roots are small and irregular and have a faded reddish color when compared to roots developed with an abundant supply of nitrogen (plate 3).

In onions, symptoms of nitrogen deficiency may appear as soon as the plants are out of the seedling stage, a condition which demands placement of some available nitrogen close to, but not mixed with, the germinating seed. Deficient plants are slow in starting, and their leaves are short, small in diameter and light green in color. Later their tips turn yellowish, a development which eventually involves entire leaves, and the plants become distinctly stunted (13, 23).

In general, nitrogen deficiency most frequently appears in vegetable crops in early spring in seasons of frequent heavy rains. It also may occur later, during maturation of crops, when cool night temperatures facilitate abundant carbohydrate accumulation and high productivity if the nitrogen supply is adequate. During periods of drouth, soluble nitrogen salts are concentrated by evaporation in the dry surface soil above the zone of root absorption, and nitrogen deficiency may result. Rain or irrigation generally moves the surface nitrogen back down to the area of effective root absorption.

PHOSPHORUS (P) DEFICIENCY

Phosphorus deficiency is most likely to become evident after crops have been grown for a number of years, with resultant utilization of the readily available forms, in soils with a low native supply of the element. In addition, use of some fertilizers increases the acidity of soil and renders phosphorus less available to plants. The importance of phosphorus is indicated by the fact that all seeds are high in it. Phosphorus is intricately associated with all of the biochemical reactions in plants. It is associated with both the accumulation and release of energy for plant

metabolic functions, and in addition is a component of many plant protein complexes. Because of the function of phosphorus in the energy transformations required for growth, plants growing in soils that are deficient in phosphorus are initially retarded in root development and this eventually results in reduced top growth and delayed maturity.

Characteristic foliage symptoms generally are less pronounced than those resulting from deficiencies of some of the other plant nutrients because of slow growth. The leaves of vegetable crops affected with phosphorus deficiency first fade to a lighter color than those of normal plants. In tomato, cabbage family plants, and sweet corn, accumulation of carbohydrates in the foliage of phosphorus deficient plants, which is not released by P for new growth, soon results in the development of anthocyanin, a purple pigment. This pigmentation may appear on the undersides of leaves or along the veins. The fibrous root system of a phosphorus deficient plant is very poorly developed. Vegetable crops have two phases in their growth cycle when requirements for phosphorus are high, the seedling stage and when fruit and seeds are developing. In recent years, use of soluble fertilizers with high phosphorus content applied in solution at time of transplanting has reduced the occurrence of phosphorus deficiency in the initial stages of growth. Normally, plants during early stages of growth contain between 200 and 300 ppm of soluble P in the fresh tissue of their upper stems and petioles. With maturity, a considerable quantity of this phosphorus is translocated to the developing fruit and seed. During early growth, a soluble P content of less than 125 ppm generally will be found associated with a developing deficiency (2).

An early symptom of phosphorus deficiency in tomatoes is development of a purplish color on the undersides of the leaves. In the veins of the leaves this discoloration may first appear in spots and later spread, entire veins finally becoming pigmented. The foliage eventually assumes a purplish tint, particularly at the tips of the leaves. The stems are slender and fibrous, leaves are small, and plants are late in setting and maturing fruit (9).

The leaves of phosphorus deficient radishes also exhibit a reddish-purple color on their undersides, (plate 3). In celery, the deficiency is exhibited by poor root development and slender stalks. Phosphorus deficiency symptoms usually appear later in the growth of onions when the nutrient is being translocated to the developing bulbs. Stunting occurs and soon the tips of the oldest leaves wilt and die. In some cases, affected onion leaves become mottled in appearance, green areas appear-

ing among the yellow and brown tissue (13, 23). With most leafy crops of the cabbage family under normal temperatures for growth, phosphorus deficiency is indicated when the undersides or the tips of the leaves take on a reddish-purple cast.

In general, phosphorus deficiency is not so widespread as formerly because fertilizer placement techniques have resulted in the maintenance of readily available phosphorus in bands near developing seedlings. After seedling roots are well established in the soil, they generally are able to obtain considerable phosphorus from levels of availability that are not adequate during early growth stages. This is particularly true on adequately limed soils where considerable quantities of high phosphorus fertilizers have been applied.

POTASSIUM (K) DEFICIENCY

Vegetables require more potassium than most crops. A satisfactory crop of celery, for example, will remove upwards of 300 pounds of K per acre. Deficiencies of this nutrient have been observed in all vegetable crops. Although soils contain from 10,000 to 40,000 pounds of total potassium, a large proportion of it is in forms that become only very slowly available to plants as the soil weathers. Symptoms of potassium deficiency vary according to the extent of the shortage of the element and in relation to the calcium and magnesium contents of the soil. Heavy liming of sandy soils low in potassium produces a potassium deficiency, due to better plant growth and also to interference of potassium absorption by the higher calcium concentration.

Although potassium cannot be associated with any particular plant compound and is entirely soluble in the plant, it has many functions; one of the best known is in facilitating the translocation of the products of photosynthesis and iron from one part of the plant to another. It acts as a "lubricant" in maintaining a high level of metabolic activity. Potassium is essential for the production of auxin, the growth regulator found in abundance in all meristematic tissue.

Without sufficient potassium, vegetables soon show reduced vigor, a greater susceptibility to disease, impairment of growth processes, and failure to develop normally, and if they are oversupplied with nitrogen, a dark bluish-green color develops. During periods of rapid growth and before fruits are maturing, the fresh stems and petioles should contain from 4,000 to above 10,000 ppm of potassium. With maturity, large quantities of potassium are translocated to the fruit and the potassium content of foliage frequently falls below 3,000 ppm. However, early in

the season a potash content of less than 3,000 to 5,000 ppm generally is associated with a developing deficiency.

In many crops with inadequate potassium, small spots occur on the margins of the leaves, resulting in marginal yellowing and later browning as the edges turn downward and die. Where there is a moderate supply of potassium in the soil, potassium starvation in tomatoes may appear first in the middles of the plants and move upward, but in very deficient soils symptoms usually appear first on the older leaves.

Potassium starved tomatoes grow slowly and have a dark bluish-green cast. The plants are stunted and the yields are small. Their young leaves become finely crinkled; older leaves turn a dark bluish-green at first and develop a yellow-green tint along their margins. This injury progresses toward the centers of the leaflets causing a bronzing of the tissue which is followed by development of large yellow areas between the veins. The affected areas occasionally turn bright orange in color and frequently become brittle, turn brown, and finally die. The stems become hard and woody and fail to increase greatly in diameter, remaining slender (plate 4A). The roots are not well developed, but remain thin, often become brown, and secondary thickening fails to occur.

Tomato fruits on plants showing extreme deficiency may ripen unevenly and lack solidity (plate 4B). "Blotchy" ripening of tomatoes is frequently related to inadequate potassium.

In sweet potatoes, a lack of potash results in poor quality roots with a high length to diameter ratio. This is due to a lack of adequate potassium to facilitate normal cambial cell division, hence a lack of growth in diameter.

Leaves of cabbage plants showing early potassium deficiency become bronzed on their edges, and later as the symptoms progress towards the center, the edges turn down and dry out, and brown spots appear in their interiors (plate 5). Cauliflower and Brussels sprouts behave similarly.

In carrots the symptoms are manifested in curled leaves. The edges of the leaves become brown, and the green in the inner portions fades to yellowish and finally becomes bronze. In cucumber and muskmelon plants, potassium deficiency symptoms are characterized by yellowing, bronzing, and drying of leaf margins. The bronzing gradually spreads into the leaf areas between the veins. In cucumbers, fruits with enlarged tip ends are characteristic (plate 2).

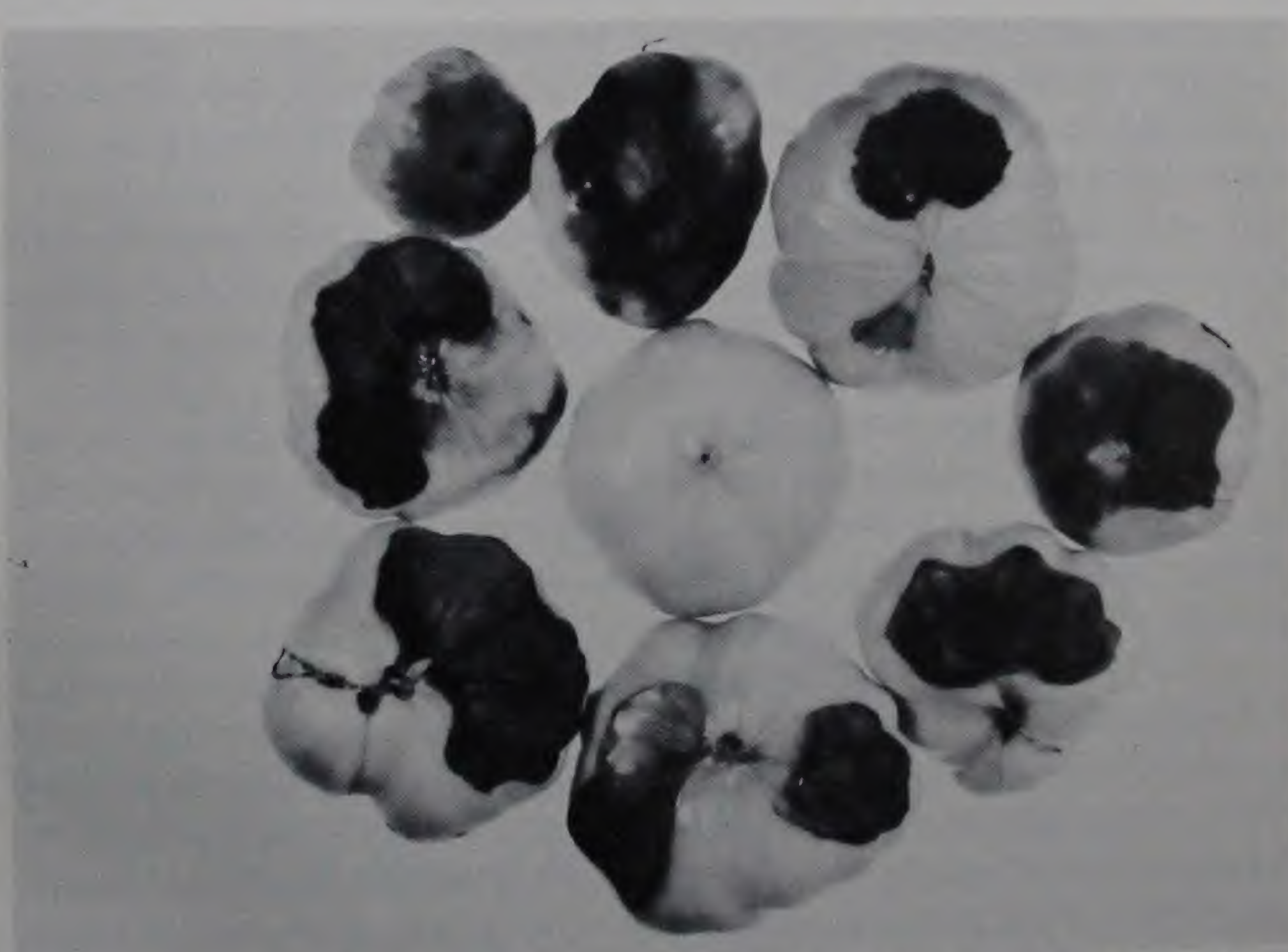
Radishes grown in potash-deficient soil exhibit a dark green color in the centers of their leaves, the edges curl downward and become pale

yellow to brown (plate 3). In beets a deficiency is manifested in a tapered root which is slender and poorly developed. In peas the plants are dwarfed, lower leaf edges become brown, and the seed develops a thickened, tough coat, giving the canned or frozen product very poor quality.

Potash deficiency symptoms in onions appear early in plants that are not stunted, the tips of the older leaves assuming a distinctly gray-yellow or light straw color which gradually progresses downward as the entire leaf wilts. The wilted areas exhibit a satiny texture and a wrinkled appearance (13, 23).

CALCIUM (Ca) DEFICIENCY

Use of limestone or superphosphate maintains an adequate calcium content in most soils. However, calcium deficiency in vegetable crops is becoming more common with the use of high analysis fertilizers low in this nutrient.



Courtesy of R. L. Carolus, Michigan Agricultural Experiment Station

Figure 1. Blossom-end rot of tomatoes is prevented by spraying plants with solution of calcium salt.

Courtesy of R. L. Lucas, Michigan Agricultural Experiment Station

Figure 2. Blackheart of celery caused by calcium deficiency. Symptoms develop in hot weather with rapid plant growth on soils high in fertilizer salts.

Recently, on soils low in calcium and high in soluble salts, the use of calcium sprays have been found to prevent the occurrence of blossom-end rot of tomatoes (figure 1). Plants grown in calcium deficient water cultures develop yellow leaves on their upper parts, indicating that calcium is not easily translocated. Calcium deficient tomato plants in water cultures are weak, flabby, and lacking in firmness or turgidity. Their terminal buds die and their stems near the terminal become spotted with dead areas. Roots are short, much branched, stubby, bulbous, and dark brown in color (17).

Celery grown on heavily fertilized soil low in calcium, under environmental conditions that result in a water stress, frequently develops brown decaying areas in its heart leaves (figure 2). This trouble has been corrected by the timely application of calcium sprays. Carrots grown on soils low in calcium and high in soluble salts frequently produce rough roots that develop pitting or "cavity spot" (figure 3) (15). This abnormality is associated with a calcium root content of less than 0.25 percent of the dry weight, and can be remedied by the use of calcium salts.

Courtesy of P. N. Maynard, Massachusetts Agricultural Experiment Station

Figure 3. Cavity spot in carrots caused by deficiency of calcium.

MAGNESIUM (Mg) DEFICIENCY

Magnesium deficiency in vegetable soils is widespread. Soils of the Atlantic and Gulf Coastal Plains, where extensive areas are devoted to vegetable growing, are particularly low in magnesium content. The deficiency results from a natural lack of magnesium in the soil, extensive leaching, and removal of considerable quantities in crops. Periodic applications of soluble magnesium fertilizers or magnesium limestone are necessary to assure crops of good quality.

Magnesium influences earliness and uniformity of maturity, size of roots and fruits, and quality of other marketable portions of crops. Vegetable plants develop a characteristic chlorosis, or lack of normal green color when the magnesium supply is insufficient. Their lower leaves are affected first; in some vegetables these are the only leaves that become decidedly chlorotic.

Tomato plants grown in soils, sand, or nutrient solutions deficient in magnesium develop leaves that are very brittle and have a tendency to curve upward. The veins remain dark green while the areas between them become yellow, the yellow color increasing in intensity with distance from the vein. The yellow areas become deeper in color and finally turn brown and break down. The symptoms are most common in the

older leaves of mature plants. As the fruit develops, the deficiency may become increasingly severe. However, there is little evidence of the abnormality on stems or fruit (plate 6).

Early stages of the deficiency in cabbage are manifested by a chlorotic, mottled, puckered appearance of the lower leaves (figure 4). The advanced stage is a more severe mottling which develops into white, bronzed, or very pale yellow areas around the edges and at the centers

Figure 4. Overwintered cabbage plant from field experiments showing symptoms of magnesium deficiency. Note the white, puckered, spotted area of the lower leaves, indicative of early stages of the deficiency.

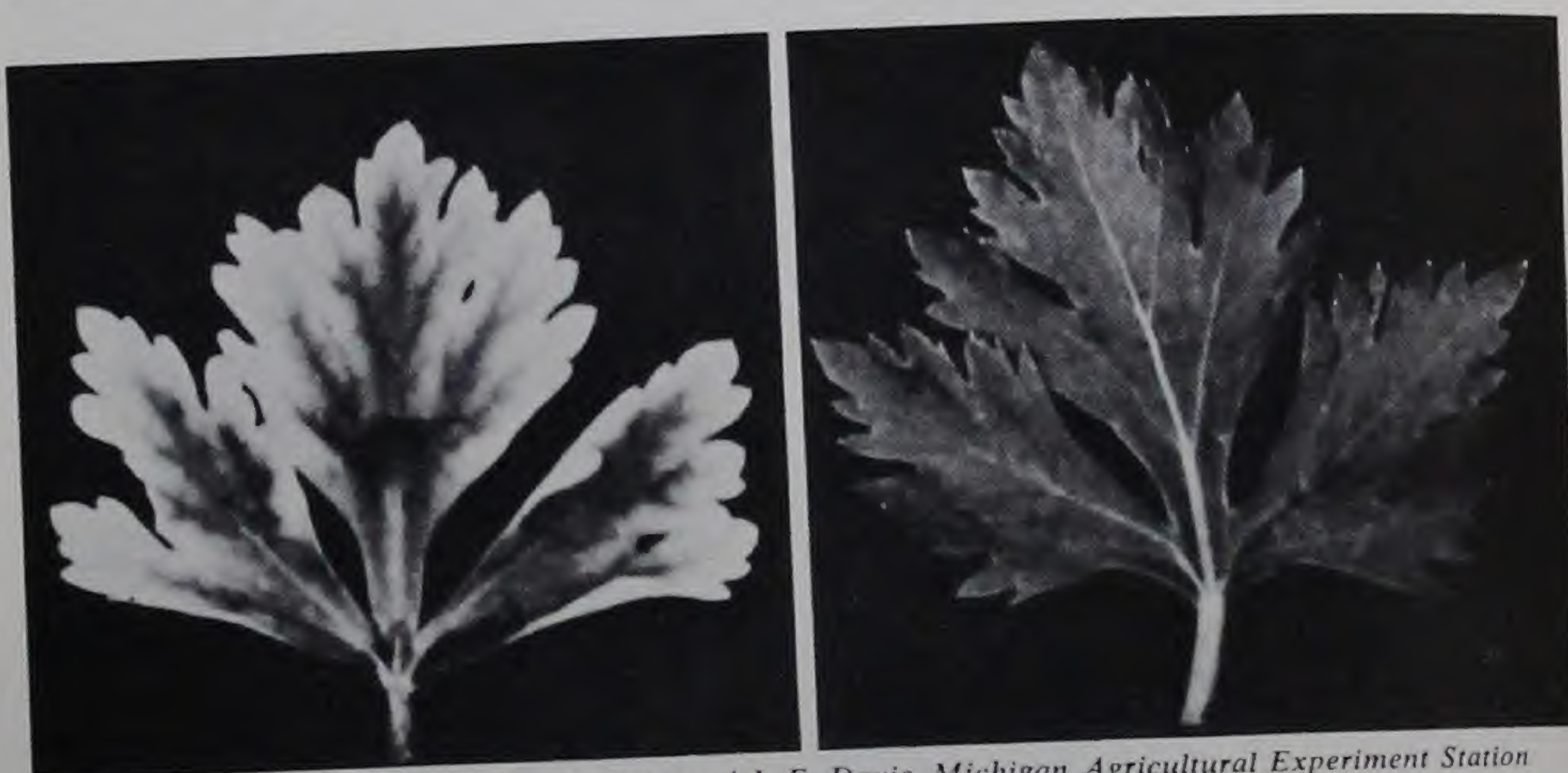
Courtesy of R. L. Carolus, Va. Truck Exp. Sta., and B. E. Brown, U. S. Dept. of Agri.

of the leaves. These areas decay and frequently fall out. The white and yellow areas at leaf edges turn brown when extreme deficiency has developed (plate 5D). If magnesium deficiency only is present, areas of dead leaf tissue mark entire leaves. If nitrogen also is a limiting factor, entire leaves will first turn light green and then become yellow before breakdown occurs in the central portions of the areas between the veins (3).

Potassium deficiency is sometimes confused with lack of magnesium. The former, however, appears as a bronzing of the leaf, the color developing into brown before the breakdown of tissue occurs. On the other hand, magnesium deficiency often appears in vegetable crops after liberal applications of either potassium or sodium fertilizer salts to the soil.

Turnip leaves from plants grown on magnesium deficient soils develop brown ragged areas around their margins which dry up and fall out, while inner areas are chlorotic and mottled (plate 7) (3).

In celery, magnesium deficiency induced by a genetic abnormality has been observed. The plant is unable to obtain adequate magnesium from the soil and the deficiency can be corrected satisfactorily only by the use of magnesium sprays (figure 5) (4). In carrots, magnesium deficiency is characterized by a fading of foliage color and the appearance of light yellow or brown spots on the tips or the lobes of the leaflets.



Courtesy of J. F. Davis, Michigan Agricultural Experiment Station

Figure 5. Magnesium deficiency in celery (left). Normal leaf (right).

Deficient plants generally are smaller than those with an adequate supply of magnesium.

Cucumber, squash, muskmelons and snap beans show the characteristic mottling and browning of foliage described for other vegetables. The first evidence of magnesium deficiency in onions grown in sand cultures is the development of irregular, elliptically-shaped areas near the ends of the leaves, almost white in color, which later disappear in a general breakdown of the affected tissues (13, 23).

Since sweet potatoes are grown on sandy soils at a low pH to control several diseases, they are especially susceptible to magnesium deficiency. The deficiency first affects the older leaves, then yellow areas develop between the leaf veins while the veins remain green (plate 8). As the deficiency becomes extreme, the older leaves turn brown and dry up while the symptoms appear in new leaves close to the tips of the vines. In the Puerto Rican type of sweet potato, the chlorotic areas between

the veins of the leaves are reddish-purple in color instead of yellow. Magnesium deficiency often reduces the yield of sweet potatoes by more than 50 per cent.

SULFUR (S) DEFICIENCY

A deficiency of sulphur is seldom found in vegetable crops grown within several hundred miles of industrial centers where the sulfur in fumes and smoke is brought down by rain. At greater distances, sulfur deficiencies may be expected to occur where fertilizers containing no ammonium sulfate, superphosphate, or other sources are used.

Sulphur deficiency symptoms of tomatoes grown in sand or nutrient cultures develop slowly. Such plants are similar in appearance to those inadequately fertilized with nitrogen. Lower leaves become yellowish-green, stems are hard and woody, and roots well developed and extensive, but both roots and stems are small in diameter. Sulphur deficient tomato plants have a remarkable capacity for stem elongation, a change which does not occur in the case of plants grown with an inadequate supply of nitrogen, phosphorus, or potassium. Stems of sulphur deficient plants, though woody and hard, increase in length but not in diameter. Such plants are high in carbohydrates and sometimes in nitrogen (18).

BORON (B) DEFICIENCY

Along with all plants, vegetable crops require small amounts of boron for normal growth. The boron content of vegetable plants seldom exceeds 50 parts per million on a dry weight basis and usually is lower. Unfortunately, the range between required amounts and amounts that are toxic is very narrow and boron salts must be applied with greater caution than is required for other plant nutrients. However, the commonly employed salts of boron are water-soluble and readily leached from soil. Toxic soil levels of the nutrient, resulting from over-application, therefore rarely persist for more than one season.

Deficiencies of boron occur in vegetable crops more frequently than deficiences of any other trace nutrient. This deficiency is found on soils formed from a variety of parent materials differing widely in physical and chemical characteristics. It is common on overlimed and sandy soils but also occurs on acid silts and clays.

Crop damage from boron deficiency may vary from slight injury to complete destruction. Cracked stem of celery and brown curd of cauliflower are physiological disturbances caused by a deficiency of boron that may result in almost total crop loss. Symptoms of malnutrition

resulting from insufficient boron have been reported from one or more regions of the United States in beets, cabbage, carrots, cauliflower, lettuce, onions, pepper, radishes, rutabagas, spinach, sweet corn, sweet potatoes, tomatoes, turnips, and possibly other vegetable crops.

The severity of boron deficiency symptoms depends on other factors beside the boron content of the soil. Soil moisture is influential; in dry seasons injury is greater from this cause. Injury to vegetable crops caused by over-liming has been attributed in some cases to boron deficiency, but the mechanism involved in rendering boron unavailable has not been explained.

Characteristic symptoms of boron deficiency in specific vegetable plants vary widely and often are pronounced. Cracked stem of celery and brown heart of table beets and turnips are very different, but both are due to lack of this element. Boron does not move readily from one part of a plant to another, and for this reason deficiency symptoms of the nutrient usually occur first in the younger root and leaf tissues.

In celery, boron deficiency first manifests itself by a brownish mottling which usually appears first along the margins of the bud leaves. The mottling is accompanied by brittleness of the stem and by brown stripes in the epidermis along the ribs. Finally crosswise cracks appear on the surface of the stalk and the tissue curls outward from these breaks. The disrupted tissue soon becomes dark brown in color. Roots of affected plants turn brown, and their laterals die back and form small knoblike appendages at their extremities. In the final stages of boron hunger, the plant dies. Under field conditions deformed plants may remain alive and new growth may appear later (plate 9) (21).

Boron deficiency in table beets (20), turnips (6), radishes and other root crops, commonly known as "brown heart," is manifested first by dark spots on the roots, usually on the thickest parts. The plant gradually becomes stunted or dwarfed. The leaves are smaller than normal and less numerous, and they gradually assume a variegated appearance. This color change develops as a mixture of yellow and purplish-red blotches over parts or all of leaves, while the stalks of such leaves usually show longitudinal splitting. Frequently the affected plant has twisted leaves and exhibits a slight shortening and discoloring of its leaf stalks in the center of its crown. The growing point may die and decay. The roots do not grow to full size. Under conditions of severe boron deficiency they remain very small and distorted and have a rough, unhealthy, grayish appearance instead of being clean and smooth. Their surfaces often are wrinkled and cracked (plate 10).

In root cross sections, boron deficiency produces the familiar symptom known as brown heart (figure 6). According to the severity of the deficiency, brown heart may vary from a few small, isolated spots to a large water-soaked area, or even a hollow center with all the inner flesh badly discolored.

In tomatoes, boron deficiency has been of economic importance in some instances but has not occurred generally. An early symptom is a blackened appearance of the growing point of the stem. The plant looks bushy, due to the growth of new leaves below the growing point. The

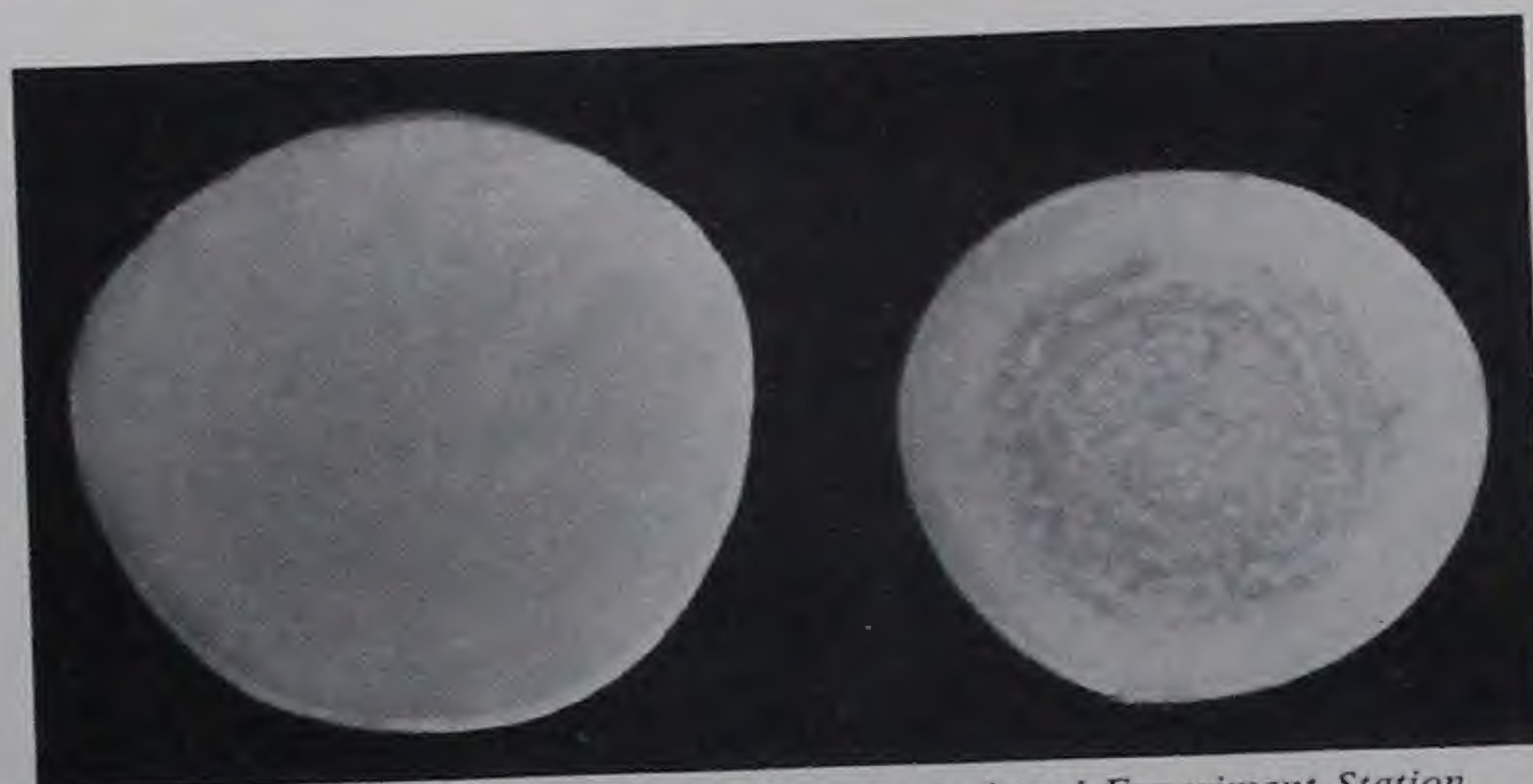


Figure 6. Interior of turnip roots showing dark center, or hollow heart, caused by a deficiency of boron. Normal turnip (left); boron-deficient turnip (right).

Courtesy of R. W. Donaldson, Mass. Agricultural Experiment Station

cotyledons, or seedling leaves, and the true leaves turn distinctly purple while the plant is young. The stems become stunted and the terminal shoot curls inward, yellows, and dies. In older plants, a yellowing of older leaves accompanied by the appearance of pink veins may occur. The conducting tissues within the veins break down and present a granular appearance (8). A striking characteristic is the extreme brittleness of the petioles, or leaf stems, and midribs. The roots show extremely poor growth and become yellow or brown. The fruits frequently suffer from darkened or dried areas, apparently owing to breakdown of tissue.

Boron deficiency in lettuce is characterized by malformation of the more rapidly growing leaves, spotting and burning of the leaf tips, and death of the growing point of the plant (figure 7) (16). The first symptoms are retardation of growth and malformation of the younger leaves. Marginal growth ceases, and this results in a folding back of the leaf tip. As spots on the leaves increase in size and number, they involve the entire leaf tip and give it a scorched appearance. The older leaves are not noticeably affected, but all young leaves, from those first affected to the growing point itself, are injured.

Boron deficiency in cauliflower first appears as small, concentric, water-soaked areas in the stem and in the center of the small branches of the curd (plate 11). The external appearance may resemble the browning in brown heart of turnips. When browning is severe, both the outer and the inner portions of the head are affected and have a bitter flavor. This discoloration of the curd may appear at various stages of

Courtesy of J. S. McHargue and R. K. Calfee, Kentucky Agricultural Experiment Station

Figure 7. Growing point of lettuce plant showing symptoms of boron deficiency. Note the curling or folding back of the young leaves and the scorched appearance of the disfigured leaf tips.

maturity, and increases with growth. In cauliflower plants affected with boron deficiency, the smaller leaves around the curd may be deformed and stunted (5).

Cabbage plants growing with insufficient boron develop water-soaked areas in their stems at the bases of their heads, similar to those found in cauliflower. These water-soaked areas usually dry out and become hollow (25).

Boron deficiency gives onion plants a characteristically stunted, distorted appearance. Leaf color varies from dark gray green to deep blue green, the youngest leaves developing conspicuous yellow and green mottlings. Shrunken areas appear, followed by ladderlike transverse

Courtesy of C. J. Nusbaum, South Carolina Agricultural Experiment Station

Figure 8. Normal sweet potato vine (left). Note the long, straight petioles, well-spaced internodes and actively growing terminal. Boron-deficient plant (right) shows a stunted, gnarled type of growth, short internodes, and curled petioles. Note the distorted terminal bud and the premature shedding of leaves.

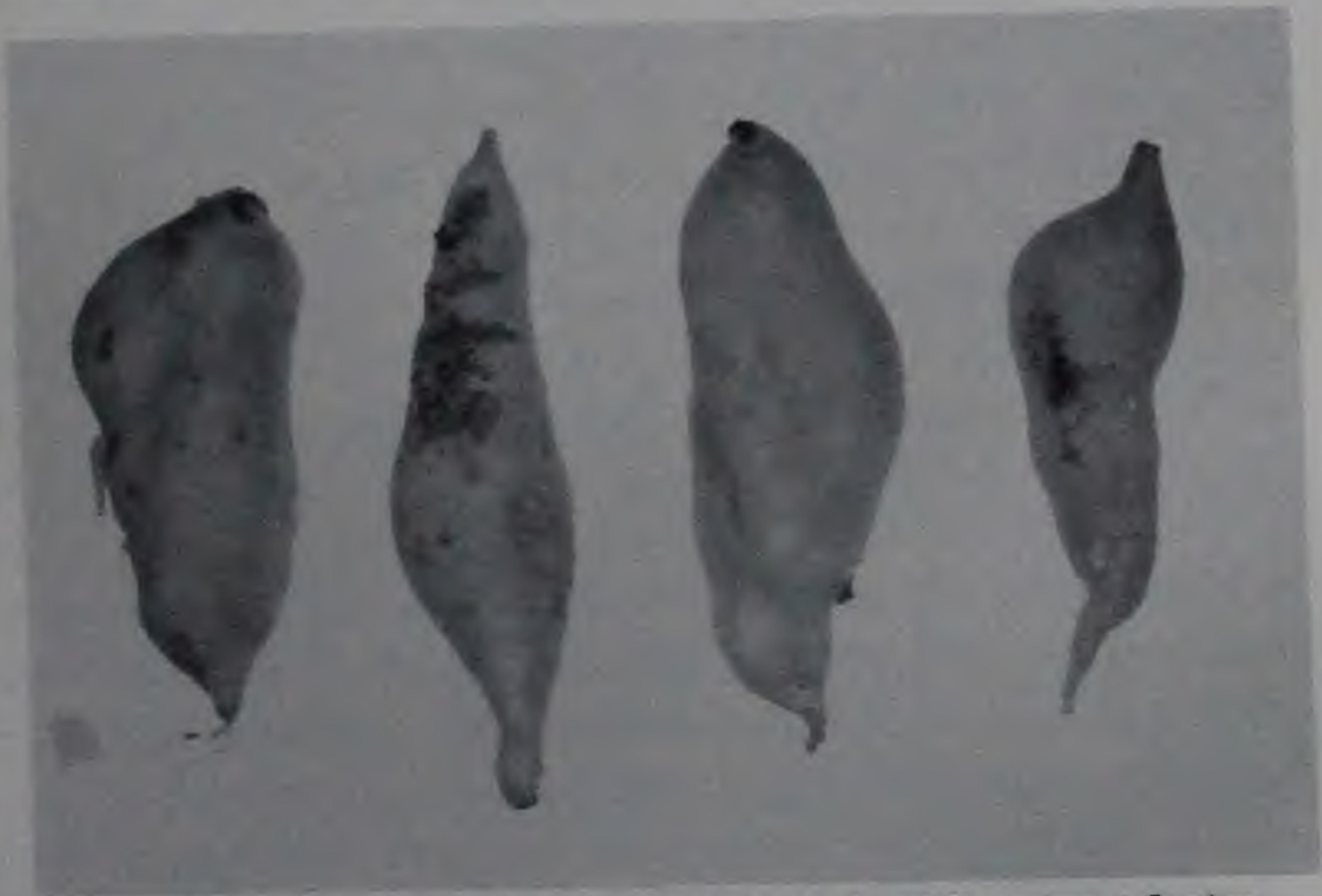


Figure 9. Sweet potato roots showing typical boron-deficiency symptoms. Note the malformation of the roots and the surface cankers covered with blackened exudate.

Courtesy of C. J. Nusbaum, S. C. Agricultural Experiment Station

cracks on the upper sides of the basal leaves. The leaves become stiff and brittle (13, 23).

Boron deficiency first manifests itself in sweet potatoes by a restriction of the terminal growth of the vines and a shortening of the internodes. As the disturbance develops, petioles become curved and the terminals become stunted and distorted (figure 8). The older leaves turn yellow and are prematurely shed. Tubers from deficient vines show varying degrees of both external and internal degeneration. They are misshapen and their skin is rough and leathery. Dumbbell shaped, lopsided, and spindle-shaped malformations are common. Severely affected tubers show surface cankers, sometimes covered with a hardened, dark exudate (figure 9). Affected tubers may show evidence of internal breakdown, similar to that produced by boron deficiency in turnips and beets. Varying in size, these internal necrotic areas occur indiscriminately throughout the fleshy parts of the tubers but seem to be most prevalent in the cambial zone near the periphery (19).

IRON (Fe) DEFICIENCY

The iron content of normal plant tissue ranges from around 25 to more than 500 parts per million, dry weight, depending on plant part and species. Plants usually obtain adequate amounts of iron from acid soils but often are unable to do so on calcareous, alkaline soils. Since few commercial vegetable producing farms are located on soils of the latter type, iron deficiency has been of little economic importance in vegetable crops. However, the deficiency has been reported in cabbage, turnips, squash, and sweet corn grown on certain calcareous Florida soils, and in beans on California soils (1).

The first symptoms of iron deficiency occur in the younger leaves and consist of a yellow mottling within the inter-veinal areas. When the deficiency persists, the affected areas become lighter in color and spread to include the leaf veins. Entire leaves become pale yellow to almost white, with little evidence of desiccation or necrosis (figure 10).

COPPER (Cu) DEFICIENCY

Copper is an essential nutrient for vegetables and other crops. Seeds are high in copper and the mineral is especially important for plants grown for seed. Available evidence indicates that copper deficiency in vegetables usually is confined to those grown on dark-colored soils, such as the Portsmouth types, and on peat and muck. Abnormal growth of vegetable crops on peat soils of Michigan and Delaware, caused by cop-

Figure 10. Iron deficiency symptoms shown by tomato plants grown in nutrient solutions. The leaf on the left is from a plant grown in a complete nutrient solution; the one on right was grown in a solution containing no iron.

Courtesy of D. R. Hoagland and D. I. Arnon, Calif. Agri. Exp. Sta.

per deficiency, has been noted. Addition of 100 to 200 pounds of copper sulfate per acre to peat soils in western New York was found necessary to produce normal truck crops. On sawgrass peat soils of the Everglades of Florida, vegetable crops will not make normal growth without addition of 20 to 30 pounds of copper sulfate per acre. Copper deficiency in plants growing on peat soils has been reported in many other parts of the world. Copper deficiency is of economic importance in vegetable production in large areas of this class of soils.

Most mineral soils contain sufficient copper to support normal crops of vegetables, except possibly some that are very sandy and leachable.

The quantities of copper sulfate that have been used on soils to correct

the deficiencies noted vary from 20 to 200 pounds per acre. Some peat soils have a high fixing power for copper compounds so that relatively heavy applications are necessary to produce the desired effect.

A deficiency of copper may not cause distinct color characteristics in the foliage of vegetable crops as do deficiencies of other nutrients. Some outstanding characteristics have been noted in field-grown plants

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 11. Tomato leaves from plants grown in nutrient solutions. Leaflet from plant grown in copper-deficient solution (left); in a complete nutrient solution (center); and in zinc-deficient solution (right). The copper-deficient plant had small stems and chlorotic leaves which were curled inward. The zinc-deficient plant had normal-sized stems with leaves resembling those of "little-leaf" of fruit trees.

in dark-colored soils, however, as well as in plants grown in nutrient solutions in the greenhouse. The leaves of affected plants do not maintain their firmness. The foliage exhibits a chlorotic condition which gives it a bleached appearance; this may be corrected by spraying the leaves with a weak copper sulfate solution. Chlorotic lettuce grown on unproductive muck soil deficient in copper has become normal after being dusted with copper sulfate.

Copper deficiency symptoms in tomatoes include very stunted growth

of shoots and exceedingly poor root development, dark bluish-green color of foliage, curling of leaves and absence of flower formation, development of chlorosis, and a lack of firmness in leaves and stems (figure 11). Leaves of copper-deficient lettuce plants become bleached and chlorotic, stems and rims of leaves being affected first (figure 12).

Onions grown on peat soils in New York exhibit copper deficiency

Courtesy of D. I. Arnon and S. B. Johnson, California Agriculture Experiment Station

Figure 12. Lettuce leaflets from plants grown in nutrient solutions. Leaflet from normal plant grown in a complete nutrient solution (left); leaflet grown in copper-deficient solution (right). Copper deficiency has caused reduced growth and malformation of the leaf, which exhibits chlorosis; the plant is weak and lacks firmness. The chlorosis appeared first on the stem and the outer rim of the leaf.

by producing abnormally thin, pale yellow scales (plate 13). Applications of copper sulfate at rates of 100 to 300 pounds per acre have increased the thickness of onion scales and changed their color from pale yellow to a brilliant brown. Copper-deficient onions lack solidity and firmness (14).

In cases of copper deficiency as extreme as on the Florida soils mentioned, vegetable plants fail entirely to grow. In less extreme cases growth is very slow and stunted.

ZINC (Zn) DEFICIENCY

The zinc content of plants usually is less than 50 parts per million of dry weight. To date, deficiencies of this nutrient have been of more economic importance in tree crops than in other plants. Reports of zinc deficiency in vegetable crops have come primarily from Florida (1), California, Washington, and Wisconsin (12). Crops affected in one or more of these states include beans, cabbage, carrots, celery, lettuce, mustard, onions, peas, spinach, squash, sweet corn, and tomatoes.

Zinc deficiency is most frequently encountered on soils having a pH of 6.5 or above and the availability of this nutrient to plants is decreased by liming. However, zinc deficiency does occur on acid soils. This is believed due to loss of available zinc through leaching, or through fixation by organic matter.

The first symptom of zinc deficiency is a mottling of the inter-veinal areas of the leaves. Such a chlorotic area becomes lighter in color and eventually necrotic, or dead, tissue appears along the margins and within the inter-veinal portions of the leaf, as in the squash leaf in figure 13. Affected plants commonly produce abnormally small, chlorotic leaves on spindly stems. In the tomato, however, small leaves may appear on stems of normal size as shown in figure 11.

Courtesy of D. R. Hoagland, W. H. Chandler and P. L. Hibbard, University of California

Figure 13. Leaf of squash plant, showing zinc deficiency symptoms, grown in nutrient solution without the addition of zinc.

Zinc deficiency symptoms in sweet corn are identical with those of field corn. They include yellow inter-veinal striping in leaves, production of light yellow to almost white bud leaves, and early desiccation and death of older leaves.

MANGANESE (Mn) DEFICIENCY

Manganese is a common constituent of soils and plants. The quantities present in both vary greatly, but there is little correlation between the total manganese in soils and that of plants growing on them. The availability of manganese to a crop is governed more by the acidity of

the soil, and the reduction state of manganese in the soil, than by the quantity present.

Deficiency of manganese in soils, as demonstrated by varied growth of plants, is confined principally to soils that are nonacid or calcareous. This deficiency has been noted in local sections of the vegetable growing areas of various parts of the country and is of economic importance in some places, especially on overlimed and calcareous soils of the Atlantic Seaboard. Manganese is sometimes deficient in acid soils, and when the deficiency occurs in decidedly acid soils it is thought to result from the leaching of soluble manganese, which may be pronounced in soils that are very sandy.

Applications of manganese to the soil have prevented chlorosis of tomatoes and other vegetable crops on the calcareous soils of Florida where crops have failed to grow without it. Healthy growth and good yields have resulted.

In the foliage of tomato plants, manganese deficiency manifests itself first as a lightening of the green color, which gradually turns to yellow, in the leaf areas farthest from the major veins. As this condition progresses, the yellow becomes more marked and extensive and the veins remain green, giving a characteristic mottled appearance to the leaf. Eventually the foliage may become completely yellow, and in many cases necrosis sets in, appearing at first as small brown pin points centering in the yellow areas farthest from the veins and expanding until larger dead areas indicate complete breakdown of the tissue. Growth is spindling, little or no blossoming takes place, and no fruit forms. Retardation of growth and chlorosis indicate failure of the leaves to function normally owing to inadequate synthesis of chlorophyll (24).

Manganese starvation in tomatoes is widespread, having been observed in regions extending from Florida to the Northern Trucking Belt. In severe cases, as in the calcareous soils of Florida, plants fail and do not produce fruit.

The characteristic, striking form of chlorosis in manganese deficient tomatoes manifests itself in greenhouse-grown plants and in plants grown in nutrient solutions (figure 14) just as it does in plants grown in various types of soils in the field.

In spinach, the chlorosis appears first at the growing tips and gradually extends throughout the plants (plate 12). The normal green color fades from the webs of the leaves, leaving them pale green to golden yellow. The green color persists longest along the principal veins. After some time elapses, white dead areas may appear between the veins of the

leaves. The gradual yellowing of spinach leaves has caused some confusion of manganese deficiency with "spinach yellows," a mosaic disease.

In table beets, symptoms of manganese deficiency are somewhat different owing to the large amounts of red and purple pigments in the plants. The leaves gradually take on a deep red to purple color instead of becoming progressively yellow. As with spinach, the color change is most definite between the veins, where eventually dead areas appear. Beets in soils extremely deficient in manganese make little growth of either roots or tops.

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 14. Manganese deficiency as exhibited in tomato leaves from plants grown in nutrient solutions in the greenhouse. Left to right, progressive stages of manganese deficiency symptoms in tomato leaflets.

Manganese-deficient snap beans grow normally for a short period, the first symptom to appear being a loss of green color in the trifoliate leaves. The yellowing does not spread to the seed leaves until late in the development of the deficiency. At first the trifoliate leaves show a faint mottling, the tissue near the veins remaining green longer than the islets of tissue between the veins. Growth is retarded when these symptoms appear, and the chlorotic leaves do not attain normal size. A few days only may elapse between the time of the appearance of first mottling and the time when the whole leaf turns a golden yellow. Small brown spots, near and parallel to each side of the midrib and veins between the lateral branches, may appear before the leaf becomes completely yellow (plate 14) (24).

When manganese becomes deficient in cucumbers, the webs of the leaves change from green to yellowish white, while the regions along the veins and midribs remain green. The stems and leaves remain small in size, weak, and slender. Frequently the blossom bud turns yellow. Cabbage (figure 15) and peppers exhibit somewhat similar characteristics. In all these plants growth is stunted and yields are reduced (22).

The manganese-deficiency symptoms described and illustrated are

Courtesy of J. J. Skinner, U.S. Dept. of Agri. and R. W. Ruprecht, Fla. Agri. Experiment Station

Figure 15. Cabbage leaves from plants grown on field plots in manganese-deficient calcareous soil in Florida. Left, from plot fertilized with nitrogen, phosphorus and potassium but no manganese. Right, from plot fertilized with manganese in addition to the other nutrients.

characteristic for most vegetable crops. Foliage symptoms exhibited in plants grown in nutrient solutions, in soil in pots in greenhouses, and in fields are very similar.

MOLYBDENUM (Mo) DEFICIENCY

The essentiality of molybdenum in plant nutrition was established as recently as 1939 and Walker's report, in 1948, of molybdenum deficiency in tomatoes grown on serpentine soils of California was the first instance of a soil deficiency of the nutrient recorded in the United States (26). Since that time, molybdenum deficiencies have been reported in

one or more states in broccoli, cabbage, cauliflower, cucumbers, lettuce, onions, peas, spinach, and sweet potatoes.

Plants require smaller amounts of molybdenum than of any other nutrient, the content of the element in normal plant tissue usually falling within the range of 0.1 to 2.5 ppm, dry weight. Molybdenum deficiency is most frequently encountered on acid soils where the nutrient is relatively unavailable to plants. However, deficiencies of the nutrient also have been reported on calcareous soils where available molybdenum supplies have been reduced by leaching and cropping.

Figure 16. Molybdenum deficiency in tomato. Note distinctive mottling and curling of older leaves, pale green color of veins, and puffed appearance of chlorotic areas.

Courtesy of Richard B. Walker, Calif. Agricultural Experiment Station

The functions of molybdenum in plant nutrition include roles in symbiotic nitrogen fixation by legumes, and in the reduction of nitrates in protein synthesis in all plants. Consequently, some of the symptoms of molybdenum deficiency, including leaf chlorosis, retarded growth, and lack of succulence, are essentially the same as in nitrogen deficiency. However, other symptoms are characteristic of molybdenum deficiency alone and assist in its identification. The early symptoms of molybdenum deficiency in beans, peas and other legumes are essentially those of nitrogen starvation. However, if the deficiency persists, symptoms more specific to molybdenum hunger develop. These include inter-veinal mottling of leaves with chlorotic areas eventually becoming puffed in appear-

ance, marginal scorching and cupping of leaves, and twisting and distortion of younger leaves (10). These symptoms are characteristic of molybdenum deficiency in most of the crops in which the disturbance has been reported and are depicted in the tomato plant shown in figure 16.

The most striking symptom of molybdenum deficiency occurs in cauliflower, broccoli and other plants of the Brassica group. The initial

Courtesy of W. R. Robbins, New Jersey Agricultural Experiment Station

Figure 17. Whiptail of cauliflower caused by deficiency of molybdenum.

symptom of this deficiency in these plants usually is the cupping of the margins of the younger leaves, accompanied by some degree of interveinal chlorosis. As the leaves develop, an abnormal twisting of the midrib occurs and the leaf tissue develops in an irregular pattern as shown in figure 17. The whip-like appearance of the developed leaf is responsible for the designation of the symptom as "whiptail."

Molybdenum deficiency in sweet potatoes results in the production of dark green, stunted leaves, often strap-like in appearance, and having prominent and distorted veins (26).

SUMMARY OF DEFICIENCY SYMPTOMS IN VEGETABLES

Symptoms of nutrient deficiencies that develop in vegetable plants growing in the field often vary somewhat from those produced in plants grown under controlled greenhouse conditions. There are several sound reasons why this should be true. Deficiency symptoms encountered in the field seldom are as extreme, or as clearly defined, as those which are artificially produced. Disease and insects often produce plant symptoms closely resembling those resulting from nutrient deficiencies, or these symptoms may partially or entirely mask the signs of plant hunger. In a similar way, symptoms of deficiency of a specific nutrient may be modified by the available supply of other nutrients. Thus, symptoms of magnesium deficiency in plants growing on soils having a high level of available potassium will be more extreme than those of plants growing on soils having a lower level. Likewise, symptoms of boron deficiency are exaggerated under conditions of high nitrogen supply. Deficiency symptoms of two or more plant nutrients may develop simultaneously and result in abnormalities which are not specific for either.

Although symptoms alone are not sufficient to warrant the report of a new deficiency within a given area, once that deficiency has been established by supporting chemical analyses of plants and soil, its extent and reoccurrence may be verified by a survey of the prevalence of the symptoms within the fields of the locality.

The characteristic symptoms of the nutrient deficiencies of vegetable crops which have been discussed in this chapter are summarized in the following key:

KEY TO NUTRIENT DEFICIENCIES IN VEGETABLE CROPS

Element Deficient

A. Deficiencies producing distinct color changes in foliage.

  B. Symptoms first apparent in young leaves.

    C. New leaves develop light-yellow color, first between veins. Later entire leaves become yellow. Necrosis and dying of tissue usually absent. Usually restricted to alkaline or overlimed soils. . . . . .Iron

    C. Chlorosis appears first between veins of new leaves and then spreads to older leaves. Veins remain green even in advanced stages of deficiency. Chlorotic areas become brown or transparent, and ultimately marked necrosis of affected tissue occurs. Deficiency more general on alkaline or overlimed soils although known on acid soils. . . . . Manganese

    C. New leaves abnormally small and mottled with yellow, or uniformly chlorotic. Necrotic, or dead, areas common. . . . . .Zinc

  B. Symptoms first apparent in old leaves.

    C. First indication, ashen gray-green leaves at base of plant. Leaves develop a bronze and yellowish-brown color. Leaf margins becomes brown and cup downward. Specks develop along veins of leaf. Tissue deteriorates and dies. Roots poorly developed and brown. Stems slender, become hard and woody. . . . Potassium

    C. Chlorosis first appears between veins of old leaves while veins remain green. Leaves becomes brittle and margins curl upward. Chlorotic areas turn brown and die. Reddish-purple pigmentation appears instead of chlorosis with some crops. Occurs most frequently on acid soils and on soils receiving high amounts of potassium fertilizer or calcium limestone. . . . . Magnesium

    C. Distinctive mottling occurs in older leaves with veins remaining light green. New leaves green at first but become mottled upon expansion. As deficiency is prolonged, puffing of chlorotic areas occurs, leaves curl inward, and necrosis sets in along leaf tips and margins. . . . . Molybdenum

A. Deficiencies affecting primarily the growing tissues of roots and stems.

  B. Symptoms seldom apparent on older growth.

    C. Stems thick and woody with vegetative growth retarded. Root tips die and sluff off with formation of small bulblike enlargements on remaining tips. New leaves chlorotic while old leaves remain green. New growth lacks turgidity. Terminal buds die in extreme cases. Fruits breakdown at blossom ends. . . . Calcium

    C. New bud leaves and petioles light in color, brittle, and often deformed in shape. Internodes short with rosetting pronounced at shoot terminals. In advanced stages, terminal buds die and new growth develops from buds below. Root growth greatly retarded with dark colored, corky areas forming in bulbous roots of such crops as beets, turnips, and radishes. Hollow stem is a common symptom in cabbage and cauliflower, and cracked stem in celery. . . . . Boron

A. Deficiencies with localized symptoms.

  B. Retarded growth with leaf chlorosis.

    C. Leaves lack turgidity and exhibit a chlorotic condition as if bleached. Growth of entire plants greatly retarded. Most prevalent on soils high in organic matter, and on peats and mucks. . . . . .Copper

	Element Deficient
C. Retarded growth with stems slender, fibrous and hard. Normal green of leaves fades to solid pattern of yellowish-green. Plant may become entirely yellow in extreme cases. Roots often show greater development than tops in earlier stages of deficiency but finally become stunted, turn brown, and die........	Nitrogen
C. Lower leaves become thick and firm and develop yellowish-green color. Stems are hard, woody, and abnormally elongated and spindly. Root system extensively developed..................	Sulfur
B. Retarded growth without leaf chlorosis.	
C. Stems slender and woody. Leaves small and often darker green than normal. With many crops, undersides of leaves develop reddish-purplish cast. Development of fibrous roots greatly restricted. Setting of fruit and maturity delayed..............	Phosphorus

NOTES ON CORRECTIVE MEASURES FOR NUTRIENT DEFICIENCIES IN VEGETABLE CROPS

Deficiencies of nitrogen, phosphorus, and potassium are readily corrected through application of a suitable grade of commercial fertilizer. On light soils, nitrogen is readily lost through leaching, and potassium only slightly less so. Side dressings with materials containing one, or both, of these nutrients often are beneficial after heavy rains. Phosphorus is rapidly fixed in an unavailable form in acid soils. Use of high phosphorus, soluble fertilizers at planting or transplanting time generally prevents phosphorus deficiency during early stages of growth.

Calcium and sulfur are rarely deficient in vegetable soils since both nutrients are supplied in common fertilizers and calcium is a principal constituent of lime.

Magnesium deficiency is readily corrected through the use of dolomitic lime. Where it is undesirable to apply lime, magnesium can be supplied to the soil in the form of soluble magnesium salts. Usually 30 to 40 pounds of magnesium oxide equivalent per acre are sufficient.

Copper deficiency occurs most frequently on peat soils of high organic matter content. The deficiency is corrected by application of copper sulfate, recommended rates varying from 20 to 200 pounds to the acre. The smaller amount usually is sufficient.

Manganese deficiency may be corrected by applying manganese sulfate to the soil at the rate of 50 pounds per acre, or by spraying the affected plants with a weak solution of manganese sulfate (0.25 percent by weight).

Boron deficiency is corrected by application of borax, or boric acid, to the soil, or directly to the plants as a spray. Rates of application vary from 5 to 50 pounds per acre, there being great variation in the tolerance and requirements of different crops for this nutrient.

Zinc deficiency may be corrected by applying zinc sulfate to the soil at the rate of 20 to 30 pounds per acre, or by spraying affected plants with a 0.50 percent zinc sulfate spray.

Iron deficiency may be corrected by acidifying the soil, or by spraying affected plants with a weak solution of iron sulfate (0.25 percent by weight).

Molybdenum deficiency may be corrected by application of sodium molybdate at rates of 0.1 to 1.0 pound to the acre. Smaller amounts are effective when applied to cauliflower seed before planting.

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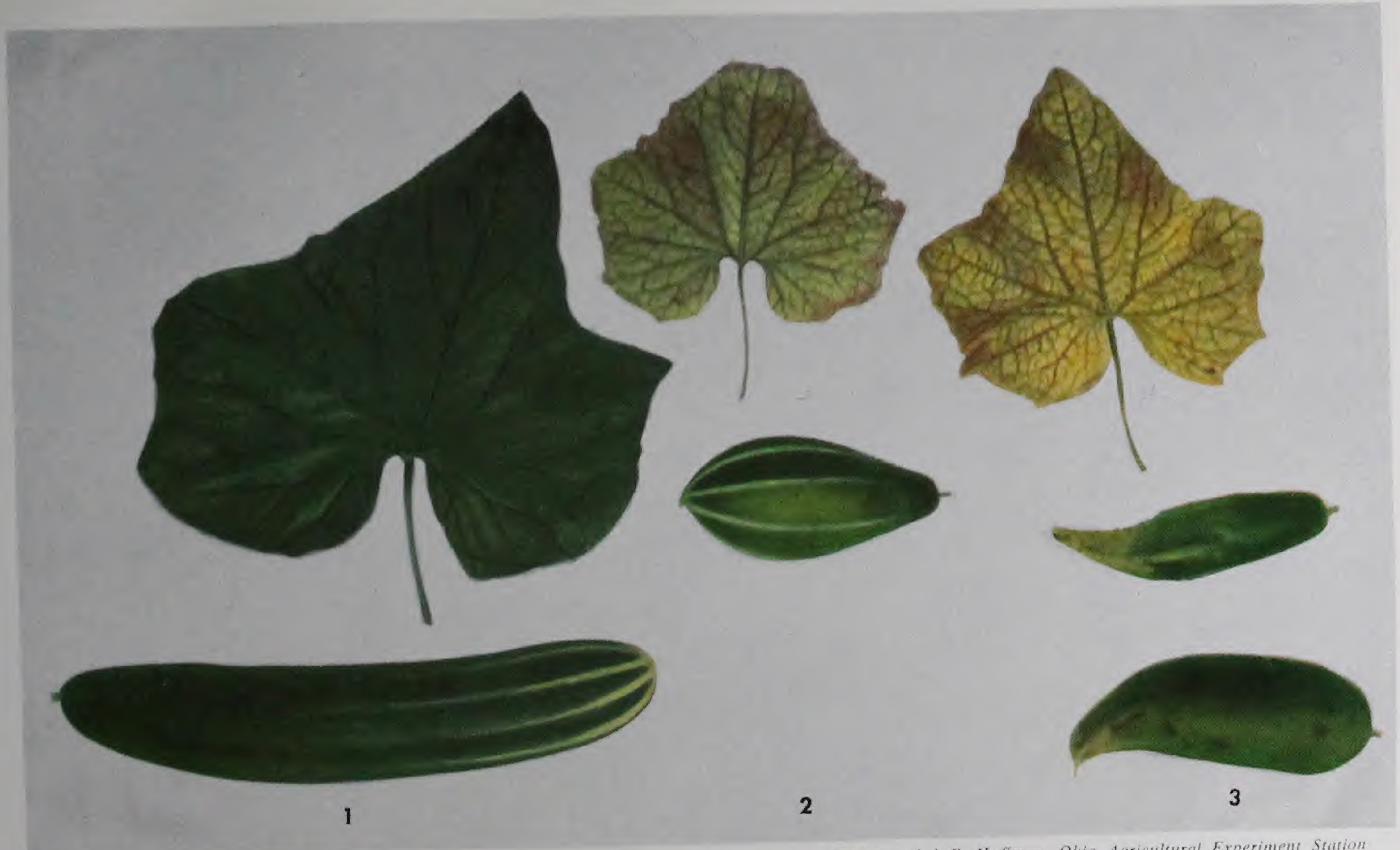
Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 1. Golden-yellow leaves with hard, fibrous, bronzed stems manifesting extreme nitrogen deficiency (left). Stems and leaves of tomato plants grown under conditions of nitrogen shortage (right) showing pale green tips of plants, purple ribs of the undersides of leaves and stems, and pale-green leaves, fading to yellow.



Courtesy of J. C. Hoffman, Ohio Agricultural Experiment Station

Plate 2. Cucumber leaves and fruits grown on Wooster silt loam fertilized with (1) complete fertilizer, (2) no potash, and (3) no nitrogen. Healthy plants (1) grew vigorously. Leaves of potassium-deficient plants (2) were bronzed and had decayed areas around their rims; fruit had enlarged tips and undeveloped stem ends. Nitrogen-deficient plants were small, leaf veins were pale green, and areas between veins were pale yellow or light brown. Blossom ends of cucumbers were pale yellow to brown and pointed.

Courtesy of S. F. Thornton and Mack Drake, Indiana Agricultural Experiment Station

Plate 3. Radishes grown in a sand-soil mixture in pots, fertilized with (1) ammonium nitrate, dicalcium phosphate, and potassium chloride; (2) potassium omitted; (3) phosphate omitted; and (4) nitrogen omitted.

A. Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station
B. Courtesy of I. C. Hoffman, Ohio Agricultural Experiment Station

Plate 4. A, potassium shortage in tomato leaves. Upper left and lower right, early stages; center, later stage; upper right and lower left, well-developed symptoms. B, tomatoes from potassium-deficient plants, left, and from normal plants, right.

A, B, C.—Courtesy of J. B. Hester, Virginia Truck Experiment Station
D—Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

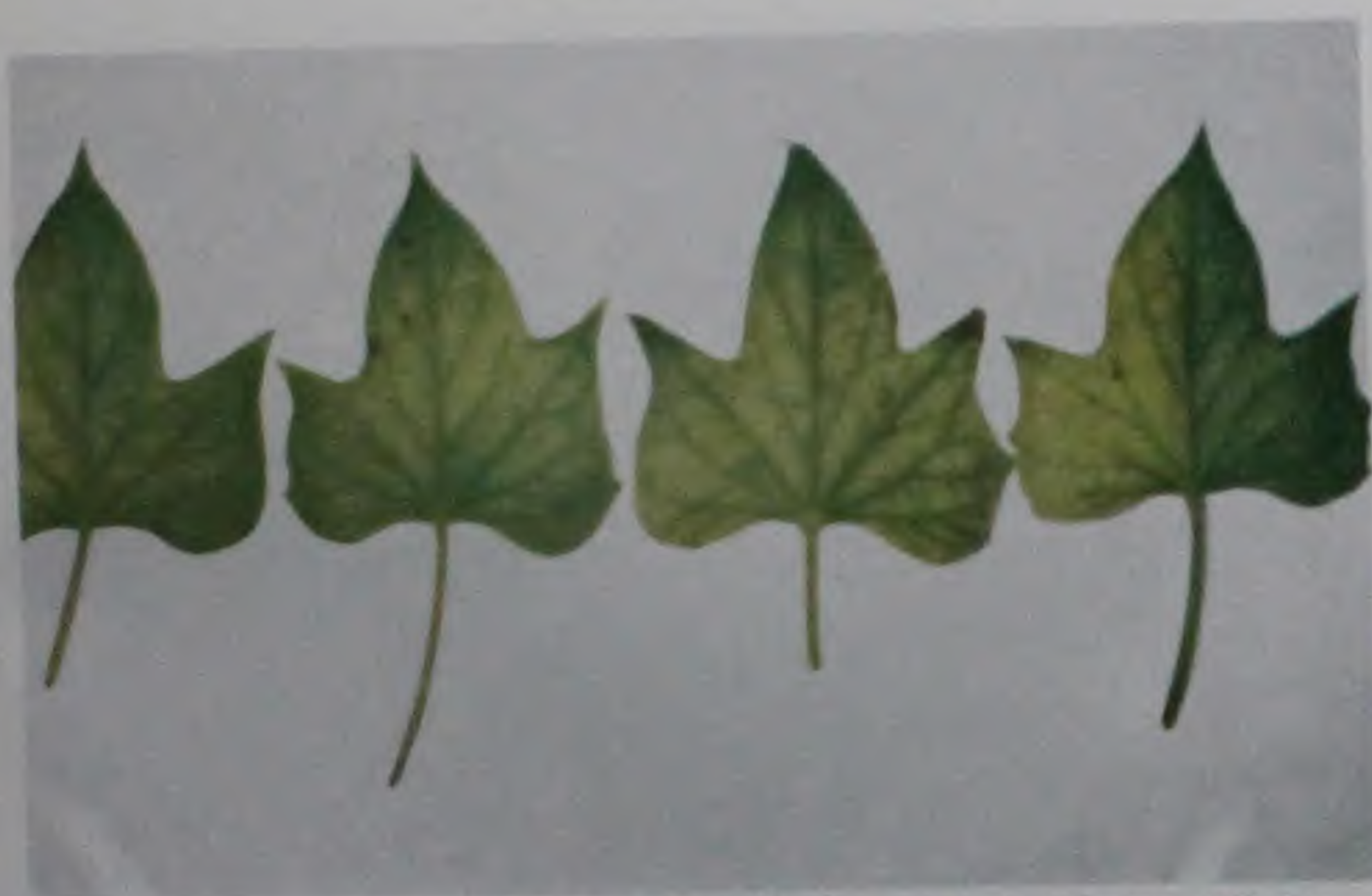
Plate 5. A, early stage, and B, late stage of potassium deficiency in cabbage leaves from plants grown in field plots on a typical southeastern truck soil. C, is a normal cabbage leaf. Leaf A shows bronzing between the veins of the inner part. Leaf B shows brown spots. D, advanced stage of magnesium-deficiency symptoms develop in sand culture. The mottled spots have turned pale yellow to white, and, with the rim of the leaf, will turn brown, decay, and die.

Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 6. Various stages of magnesium deficiency symptoms in tomato leaves from plants grown in nutrient solution and sand cultures: early stage in leaf (top), severe stage in leaflet (lower left), intermediate stages (center and lower right). The early deficiency symptoms are exhibited by pale-yellow areas between the veins of the leaves. In the later stages these develop into brown and black areas.

Courtesy of R. L. Carolus, Virginia Truck Expmt. Sta., and B. E. Brown, U. S. Dept. of Agri.

Plate 7. Leaves (left) from normal and (right) from magnesium-deficient turnip plants, both grown in field plots at the Virginia Truck Experiment Station. The outline of the magnesium-deficient leaf is ragged owing to disintegration of the outer edge. The inner areas are very chlorotic.



Courtesy of Soils Department, New Jersey Agricultural Experiment Station

Plate 8. Magnesium-deficient leaves from field-grown sweet potato plant. Terminal leaves on same vine were normal in color.

Courtesy of W. L. Powers, Oregon Agricultural Experiment Station

Plate 9. Celery plants grown in boron-deficient soil. (1) Healthy plant grown in soil to which boron was added; (2) and (3) plants showing crack stem and decay due to boron deficiency.

Courtesy of W. L. Powers, Oregon Agricultural Experiment Station

Plate 10. External and internal appearances of beets grown in a boron-deficient soil.

Courtesy of C. H. Dearborn, H. C. Thompson, and G. J. Raleigh, N.Y. (Cornell) Agri. Experi. Station

Plate 11. Cauliflower grown in a boron-deficient soil, showing hollow stem and bronzing, symptoms of boron deficiency. Normal plant grown in soil receiving 10 pounds of borax per acre (left); plant grown in soil to which no borax was added (right).

Courtesy of Soils Department, New Jersey Agricultural Experiment Station

Plate 12. Manganese deficiency symptoms in field-grown spinach plant. Note mottling and crinkling of leaves and spots of desiccated tissue.

Courtesy of J. E. Knott, N. Y. (Cornell) Agri. Experiment Station

Plate 13. Effect of copper sulfate on color of scales of onions grown on copper-deficient peat soil. Left to right: No copper, 100 pounds, 200 pounds, and 300 pounds of copper sulfate per acre. Copper increased thickness of scales and the brown color.

Courtesy of J. B. Hester, Virginia Truck Experiment Station

Plate 14. Leaves from normal and manganese-deficient bean plants grown on a neutral truck-crop soil at the Virginia Truck Experiment Station. Normal leaf (left); leaf showing early stages of manganese deficiency (center); leaf showing late stages of manganese deficiency (right).

Chapter IX

Nutrient Deficiencies in Deciduous Tree Fruits and Nuts

By John C. Cain and C. B. Shear *

PLANTS do not eat and drink at periodic intervals like animals nor can they search for food or change their habitats for better living conditions. They must obtain all of their necessities of life by physical contact with the immediate environment in which they are located or fail to survive. Thus, man must insure the adequacy of these necessities if he is to reap a good harvest. This normally is done by selection of soil and climate in which to place the plants; protection from competition with each other and other plants by planting, weeding, and other cultural practices; protection from ravages of insects and disease; and finally by provision of additional water and mineral nutrients when needed. This is agriculture in a nutshell.

Fortunately most plants will survive under a rather wide range of availability of these necessities, but *mere survival* of a plant might mean starvation for man and animals depending on it for food. Thus, factors favoring growth must be provided in such quantities that the plant can produce a surplus of vegetation and fruit above that which is necessary for survival. Modern living standards demand top performance in crop production; hence, we must seek maximum performance from our plants.

The following pages are devoted to the understanding and recognition of mineral nutrient requirements of deciduous fruit and nut trees for best agricultural production.

THE SOIL

Broadly speaking, mineral nutrients perform the same collective functions in all plants and animals. They serve as building materials for tissue construction, they form chemical compounds needed for transportation

* John C. Cain is Professor of Pomology at the New York State Agricultural Experiment Station, Geneva, New York. He prepared the section on fruits. C. B. Shear is Plant Physiologist, U. S. Department of Agriculture. He prepared the section on tree nuts.

and communication services within the individual organism, and they provide the necessary chemical environment and energy transformation mechanisms for the biochemical processes of metabolism. The plant has access to these minerals normally only through the soil, although significant quantities of sulfur and nitrogen (as ammonia) may be acquired directly from the atmosphere.

The ideal soil serves as an anchorage for the plant, as a porous pliable medium through which roots can penetrate and increase in size, and as a storage reservoir for water, air, and mineral nutrients. It also serves as a "homogenizer" for these materials, so that air, water, and mineral nutrients are in contact with all parts of the plant root system, and as a buffer against extreme and rapid fluctuations in temperature.

The soil particles themselves are composed of minerals and are the natural source of the mineral elements essential for plant growth. However, these particles are very insoluble and rates of liberation of many elements are very slow. Over the many thousands of years during the formation of soil from its parent bed rock in the earth's crust and the development of native vegetation, "virgin" soils accumulated rich stores of minerals available for plant use. Since this natural vegetation returned its mineral content to the soil upon death, the only losses were through erosion and leaching which were minimized under these conditions. With continued agricultural use, leaching and erosion losses are increased and considerable quantities of minerals are removed from the soil in plant products harvested. Thus, "used" soils often become depleted of natural minerals while native soils frequently are deficient in certain minerals needed for maximum crop production. Furthermore, some mineral nutrients are lost from the soil by these processes more rapidly than others. Therefore, no consistent relationship exists between the minerals present in different soils even though similar in origin and in period of agricultural use, because of the varying ways in which they are lost under different cropping systems and climatic conditions. We must find some way to tell when and what particular nutrient elements are in deficient supply for maximum production.

IMPORTANCE OF SYMPTOM RECOGNITION

Plants are said to show "hunger signs," as implied by the title of this book, and mineral nutrients frequently are called "plant foods." However, the plant physiologist prefers to use the term mineral nutrients and reserve the word "food" for those nutrient materials providing energy. Animals must have energy foods, which are derived from plants or other

animals which in turn get them from plants. All energy providing foods are manufactured by plants, which in turn store the energy from the sun in these foods. When properly supplied with the other essentials not mentioned plants use some of these energy foods (carbohydrates, fats, and proteins) in their own metabolism but manufacture a surplus, which man and animals use for food. Thus, "hunger signs" in plants are symptoms of mineral nutrient deficiencies. These mineral deficiencies are revealed by various "symptoms" which are abnormal appearances in plant coloration or growth. Fortunately, most of the essential nutrients perform such specific functions in the plant that a deficiency of any one usually can be recognized and distinguished from another by careful and repeated observation and familiarity with what to look for. These symptoms have been occurring, of course, since plants first evolved but only recently, through observation, experimentation, careful description, and photography, has man been able to associate deficiencies of certain elements with their characteristic symptoms. This enables him to apply corrective measures in the form of fertilizers and to avoid crop failures caused by lack of plant nutrient elements. Thus, recognition of "hunger signs" in plants is as important to farmers as recognition of symptoms of malnutrition in animals and humans is to veterinarians and physicians.

COMPARISON OF PERENNIAL AND ANNUAL CROPS

Annual crops usually complete their productive growth from seed to maturity in one growing season and a large part of their growth is harvested or removed from the land. Furthermore, most of these crops obtain the bulk of their minerals from a relatively shallow layer of top soil, from which continuous cultivation and sometimes irrigation increases erosion and leaching losses. Thus, mineral depletion of the soil, and annual fertilizer requirements, are considerably greater with field crops than with perennial crops like fruits and nuts.

In addition, the relatively rapid growth of annual crops during a short period of time, where virtually the entire nutrient content (the original mineral content of the seed is small) must be taken from the soil, imposes a severe demand on the "rate of supply" by the soil. This creates deficiencies in some crops where others, which are able to obtain adequate supplies at a slower rate over a longer period of time, would not suffer on the same soil.

Tree crops usually have some degree of root activity throughout the year although it is much lower during winter. Their roots extend deep into subsoil areas, and the bulk of the plant body remains intact year

after year. Thus, by means of storage of surplus nutrients, by internal movement of food and nutrients from one plant part to another, and to some extent by re-use of certain nutrients from one year to another, perennial plants, such as fruit and nut trees, do not exhibit rapid or sudden changes in nutrient status. Development of deficiency symptoms in them is slower and more subtle, sometimes gradually increasing in severity over a period of several years. However, this factor enables the alert orchardist to detect deficiencies and apply corrective measures before serious crop failures result. Except for young plantings on severely deficient soils, usually two or more years elapse between the first appearance of deficiency symptoms and the time when the deficiency is severely affecting tree performance.

The surface foot or so of many soils, especially those which have been used for annual crops for long periods of time, may be seriously deficient in some mineral nutrients, notably calcium, potassium, and magnesium, whereas at greater soil depth there may be adequate supplies. On such soils, young tree plantings, having limited root systems, may show deficiency symptoms whereas older trees seem to "grow out of it." The reverse also may be true on some special soils with high "fixation" capacity. The surface soil may have its fixing capacity saturated by fertilization and provide available potassium, but as the tree grows older and the bulk of its roots are in deeper soil a deficiency may develop.

OTHER FACTORS AFFECTING DEFICIENCY SYMPTOMS

Numerous other factors may limit tree growth in the presence of adequate nutrition and sometimes result in symptoms which may be mistaken for nutrient deficiencies. The most common of these are drought, mechanical injury of trunks, systemic diseases, herbicides, and under some conditions toxic concentrations of other elements. These hazards will not be discussed in great detail, but the diagnostician must be constantly alert for them. He must remember at all times that no amount of fertilization will improve plant performance if some other factor essential for good growth is causing a "bottleneck" even though the plant may show some symptom of nutrient deficiency.

Mechanical injury, such as partial girdling, root damage, low-temperature injury to the trunk or branches, mouse or rabbit feeding, or like damage usually is distinguished by marked contrast in appearance of adjacent trees, or individual branches on the same tree, whereas deficiencies which result from a lack of nutrients available to the root

system usually occur more consistently from tree to tree within an area. Although, due to soil variations, nutrient deficiencies sometimes are "spotty," more than an individual tree or branch should be affected before shortages are given serious attention.

Virus diseases, especially in stone fruit, frequently are confused with nutrient deficiencies and in special cases can be distinguished only by evaluation of two or more characteristic symptoms. However, as a general rule, chlorotic leaf spots due to viruses have sharp, abrupt boundaries and frequently are angular in shape. Chlorotic areas due to nutrient deficiencies usually change gradually in color around their boundaries and are not sharply angular in shape. Exceptions prevail to every rule. Proficiency in visual diagnosis improves with experience and familiarity with symptoms.

Definition of Terms: The following terms are frequently used in descriptions of symptoms and are defined here for convenience:

Shoot.—The most recent terminal extension of a twig or branch; current seasonal growth.

Internode.—The space along the shoot between the point of attachment of two adjacent leaves.

Terminal.—The outermost extremity of a branch or shoot along its axis.

Petiole.—That part of the leaf between the blade and the shoot by which the leaf is attached to the shoot.

Mid-rib.—The main vein or veins of the leaf extending from the petiole to the leaf tip.

Lateral veins.—The large veins connected directly to the mid-rib and extending toward the leaf margins.

Fine veins.—The "network" of fine veins near the terminal extremities of the leaf vein system.

Chlorosis:—Yellowing or loss of green color by all or part of the leaf. Lack of chlorophyll.

Pigmentation.—Development of additional color, usually red or purple, other than chlorophyll.

Necrosis.—Death of tissue.

Rachis.—In pinnately divided leaves such as those of the walnut and pecan, the rachis is the extension of the petiole or leaf stem to which the leaflets are attached.

VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES

The following descriptions of symptoms of mineral nutrient deficiencies are based on the assumption that complicating growth factors already discussed or other nutrient shortages are not severely limiting tree performance. In all cases where comparative terms are used, a healthy plant condition is assumed to be the standard of reference.

VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES *(Continued)*

NITROGEN (N) DEFICIENCY

Probably most frequent in occurrence of all nutrient deficiencies, nitrogen shortage is almost invariably associated with a reduction in vegetative growth and paleness of leaf color. The symptoms usually are fairly uniform over the entire plant and individual leaves exhibit a uniform color over their entire surface. Judgment of leaf size and color, and of shoot growth, should be made after a growth flush is completed and leaves are mature. The reduction in leaf color of deficient trees usually is more marked as the season progresses resulting in earlier defoliation and brighter fall coloration. Thus, late in the growing season is the best time to judge nitrogen deficiency. Leaf color differences are less marked on cherry, peach, and pear trees, whereas marked reduction in leaf color may appear by mid-season on apple and plum. Fruits usually are smaller and mature earlier (plates 1, 2, 13).

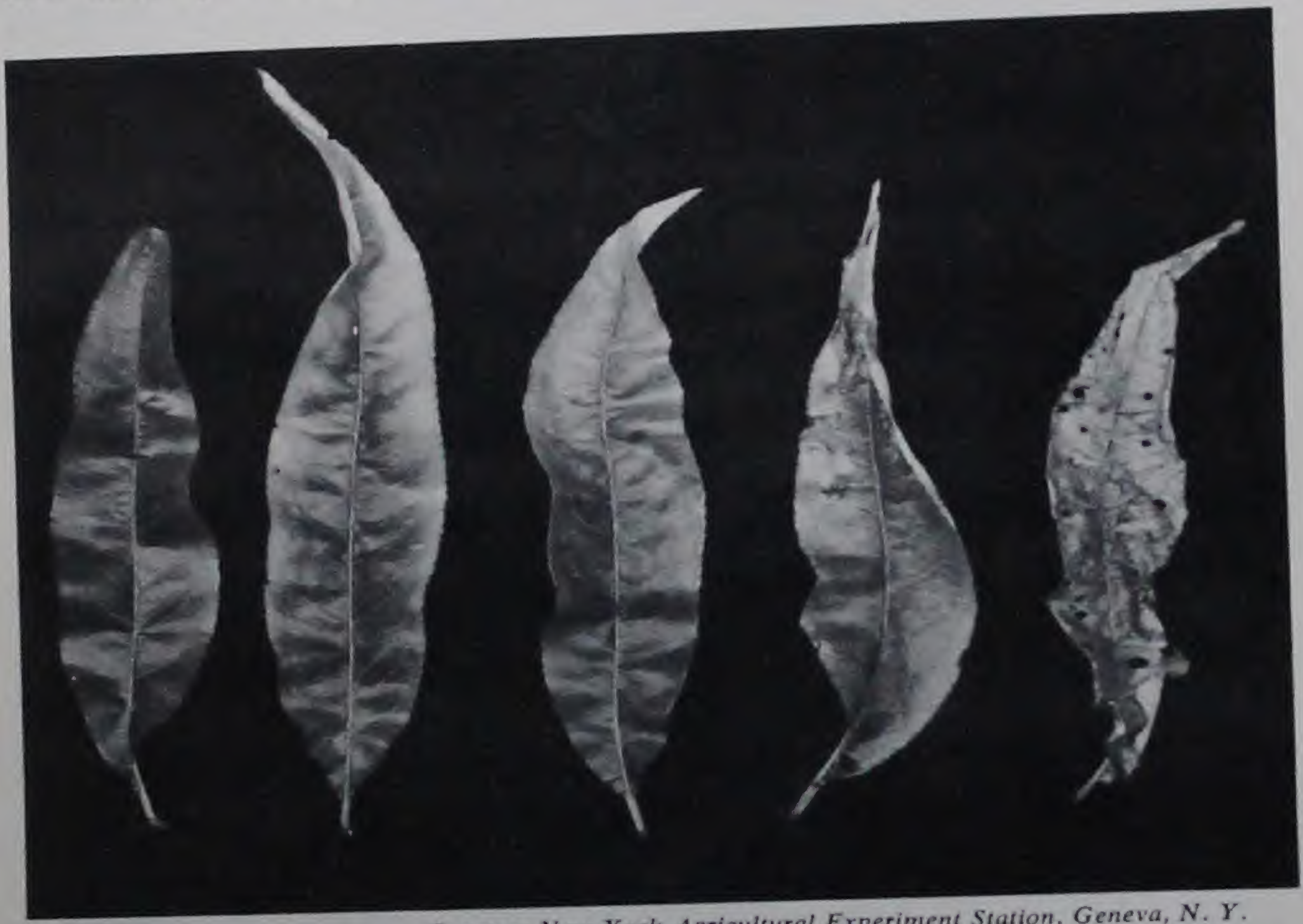
PHOSPHORUS (P) DEFICIENCY

Phosphorous deficiency rarely is encountered in commercial fruit orchards. The symptoms are similar to those of nitrogen deficiency in that both growth reduction and uniform paleness of foliage occur. However, the following differences should be carefully observed: (a) Very young expanding leaves and new shoots frequently show a purple pigmentation especially along leaf margins and the lower sides of main veins. (b) These symptoms frequently become less marked in late summer after active vegetative growth is complete and the slow but steady rate of phosphorous absorption by the roots catches up with growth demands. Thus, the best time to evaluate possible phosphorus deficiency symptoms is early in the season during active vegetative growth and, when possible, after insuring that the nitrogen supply is adequate.

POTASSIUM (K) DEFICIENCY

The outstanding symptom of potassium deficiency is "marginal scorch" of older leaves, but reduced shoot growth and leaf size also usually occur. On some species, notably cherry, plum, and peach, an upward lateral curling of the leaves is evident before scorch appears. The necrotic lateral margins of the older leaves vary in color from almost black in pears to various shades of brown on apples, and may be very light or dull gray on peaches and cherries. This necrosis is preceded by a dull darkening or "etched" appearance of the lower sides of the leaves

along their lateral margins and usually by an upward curling of the leaves of cherry, pear, plum, and peach. The upward curling is not so prominent on apple but an edge darkening or browning appears on the upper sides of the leaf margins. A distinguishable decrease in severity of symptoms almost always occurs in the youngest leaves. An increase in severity also develops in dry seasons, and the symptoms are most marked late



Courtesy New York Agricultural Experiment Station, Geneva, N. Y.

Figure 1. Potash (K) deficiency on Halehaven peach leaves. From left, normal; right, progressive degrees of symptom development.

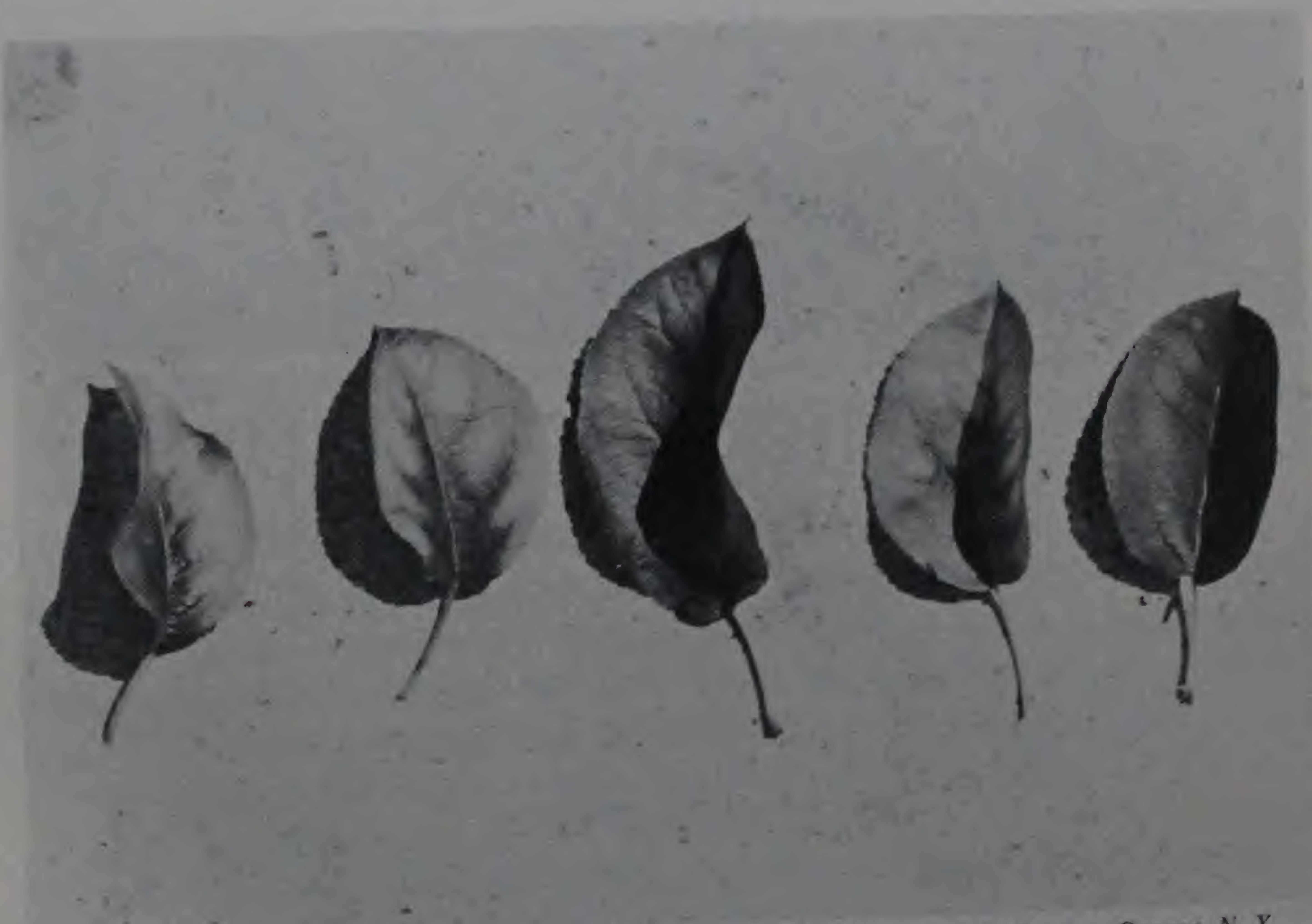
in the growing year. On some varieties and species, chlorosis or paleness of color may precede necrosis from the lateral edges toward the midribs of leaves. A heavy fruit crop usually accentuates the appearance of symptoms. Fruit may be small and somewhat immature at usual harvest time (plates 3, 4, 5, 6, 7, 12, 13 and figure 1).

MAGNESIUM (Mg) DEFICIENCY

Magnesium deficiency is characterized by inter-veinal "islands" of chlorosis and necrosis starting between main lateral veins between leaf margins and midribs. This results in a characteristic "herringbone" pattern of chlorosis or necrosis on the oldest leaves. It first appears as

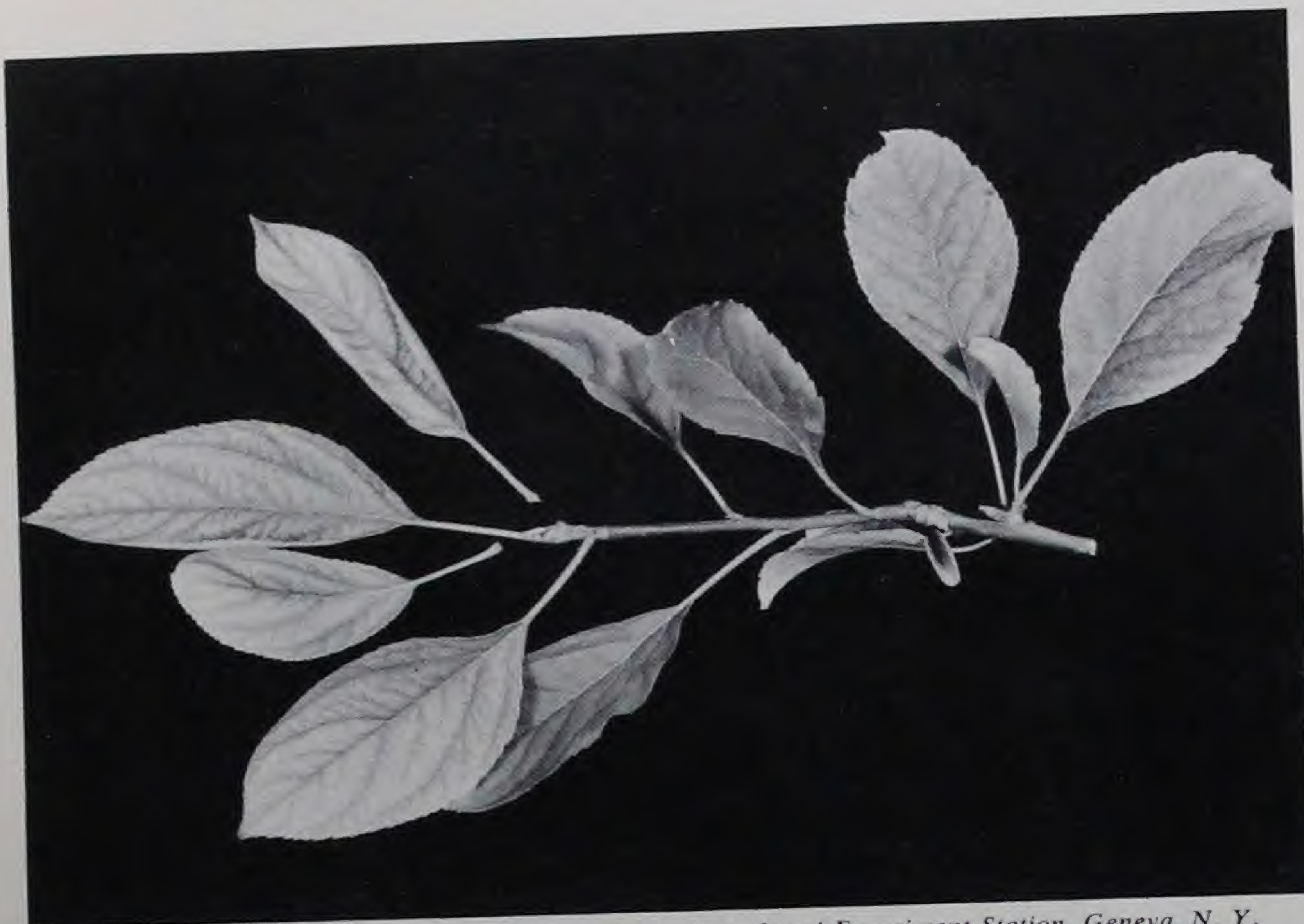
VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES *(Continued)*

a fading of green color at the terminal extremities of the very finest veination network on the oldest shoot leaves. These areas may become yellow (typical of most species) or darken, and become pigmented or necrotic without chlorosis. The coloration varies with variety and species but the pattern is fairly characteristic. The severity of the symptom decreases from basal to tip leaves on a shoot, and increases toward the end of the growing season. Early loss of more severely affected leaves usually occurs and fruit may mature and drop early. Frequently V-shaped areas of green appear that are centered along the midribs with their apexes toward the tips of affected leaves. The area outside such a V may be yellow, pigmented, or necrotic. Symptoms frequently are accentuated by potash fertilization. Necrotic areas may be nearly black in pears and cherries, yellow to brown in apples, but the V-pattern is more typical of plums, peaches, and blueberries with varying degrees of yellow, red, or purple pigmentation on the outside of the V's. In late stages, the necrotic spots may break out leaving holes in the leaves, or may encompass all leaf tissue to the margin. In the latter case the symptoms may



Courtesy New York Agricultural Experiment Station, Geneva, N. Y.

Figure 2. Magnesium (Mg) deficiency on McIntosh apple. Note darker V-shaped pattern centering on midrib.



Courtesy New York Agricultural Experiment Station, Geneva, N. Y.

Figure 3. Iron (Fe) deficiency in young Golden Delicious apple. Youngest leaves are lightest in color, with progressive darkening in older leaves. Chlorotic leaves show clean cut fine veins against pale background.

resemble the severe marginal scorch of potash deficiency (plates 8, 9, 10, 12, and figure 2).

IRON (Fe) DEFICIENCY

Iron deficiency is characterized by inter-veinal chlorosis (yellowing) of young leaves at the tips of shoots. In severe cases the new leaves may unfold completely devoid of green color, but the veins usually turn green later. Green color slowly develops with increasing age of leaf and usually the very finest network of veins is distinctively green against a yellow background. Although the ultimate length of shoots may be less and leaf size smaller than normal, no other marked abnormality occurs in the shape of the growing tip. Usually no growing point "rosette" develops and older leaves frequently appear normal or much less chlorotic than those at the tips of shoots (figures 3, 4).

MANGANESE (Mn) DEFICIENCY

Manganese deficiency is characterized by a pattern of leaf chlorosis somewhat between that caused by magnesium deficiency and that caused

VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES *(Continued)*

by iron deficiency; however, unlike iron deficiency it usually does not appear on young, newly expanding leaves, nor are the finest veins outlined. Unlike magnesium deficiency, manganese deficiency usually does not cause inter-veinal necrosis (except in severe cases on some species), and unlike both manganese and iron, it usually causes no outstanding consistent gradient in its severity between the basal and apical parts of the shoots. It may appear on any or all mature leaves. Where symptoms are well developed, usually broad bands of normal green color remain along the larger veins of the leaves. It may be mistaken for early stages of magnesium deficiency on some leaves, but careful inspection of a number of shoots will reveal that magnesium deficiency symptoms are likely to be confined to the oldest leaves. Mn deficiency symptoms are likely to appear soon after the leaf is fully expanded, and persist relatively unchanged throughout its life. Terminal leaves are not likely to show symptoms until after the terminal bud is formed. The best time to observe this deficiency is about when terminal shoot growth ends (plate 11 and figure 5).

Courtesy New York Agricultural Experiment Station, Geneva, N. Y.

Figure 4. Iron (Fe) deficiency on mature shoot of apple. Note fine vein detail on lighter colored young leaves, as contrasted to more normal older leaves.

Courtesy New York Agricultural Experiment Station, Geneva, N. Y.

Figure 5. Manganese (Mn) deficiency in Elberta peach, progressing from normal young leaves on left to extreme deficiency on older leaves at right.

COPPER (Cu) DEFICIENCY

Copper deficiency, sometimes called "dieback" or "witches broom," is characterized by early cessation of terminal growth and partial dying back of terminal shoots. Buds growing out below dead areas ultimately result in a bushy appearance of new growth. The leaves may be chlorotic and small, and some species show various stages of mottled pigmentation, brown or bronze areas and necrotic spots in severely affected leaves. The most severely affected leaves are near shoot tips. This deficiency is relatively rare, probably because of the minute quantities required and the common use of fungicides containing copper which may be absorbed by the leaf.

BORON (B) DEFICIENCY

The most characteristic symptom of boron deficiency usually is found on the fruit. This occurs as internal browning and "corky" areas or spots in the flesh, and sometimes as cracking or "corky" tissue in the skin. However, in more severe cases vegetative growth is affected. Terminal

VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES *(Continued)*

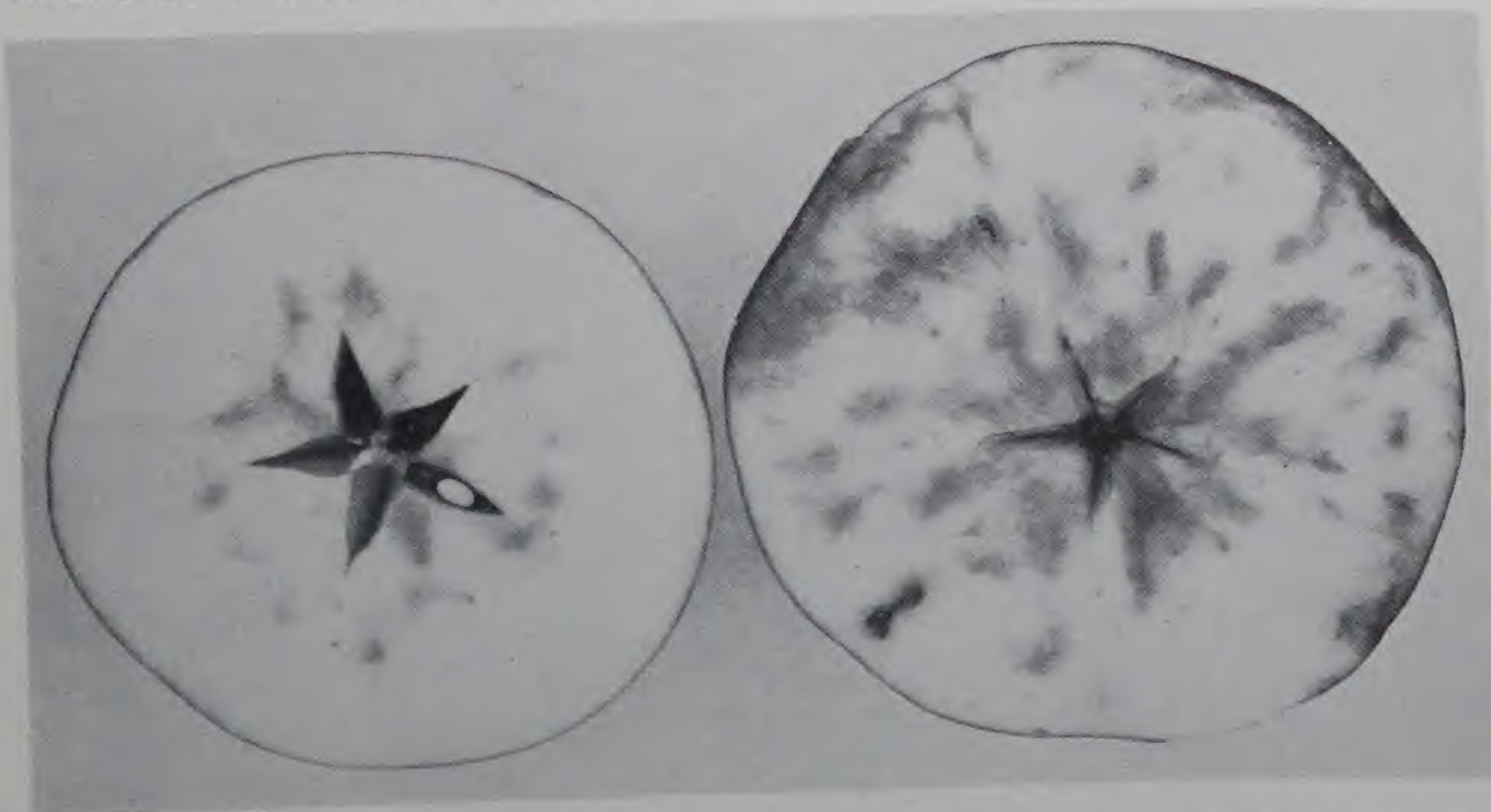


Figure 6. Boron (B) deficiency symptoms in apple: Internal cork in McIntosh fruits. This type of boron deficiency usually develops in late summer.

Courtesy of A. B. Burrell, Cornell University.

Figure 7. Boron (B) deficiency symptoms in Oldenburg apple, about 5 weeks after petal fall, showing both internal and external cork due to insufficient boron.

buds may abort or fail to open and a portion of the twig may die back. Terminal leaves, sometimes malformed, dwarfed, and curved upward, may become "boatlike." Leaves usually are not distinctly chlorotic, although some variations in color may appear. Apples and apricots seem more sensitive than other fruits, and since boron deficiency usually occurs only in certain areas, these fruits should be used where possible to anticipate its need by other fruit. Fruit symptoms usually occur before vegetative symptoms are apparent (figures 6, 7, 8).

Courtesy of A. B. Burrell, Cornell University.

Figure 8. Boron (B) deficiency in McIntosh apple. Rosette and dieback; leaves are narrow, thick, and have smooth rather than serrated margins.

ZINC (Zn) DEFICIENCY

Zinc deficiency commonly is called "little leaf" or "rosette." It is characterized by these features at the tips of new growth and usually is accompanied by a chlorosis which may resemble that of iron deficiency. However, it is readily distinguished by a conspicuous shortening of the internodes toward the tips of shoots and small narrow leaves. Frequently the leaves are bent sharply upward on either side from their midribs. In severe cases older leaves may fall, leaving tufts or "rosettes" of leaves at the tips of shoots. This deficiency is relatively rare in deciduous fruit areas except in some special western soils and on sandy coastal plains (figures 9, 10).

OTHER ELEMENTS

Deficiencies of other elements essential in plant growth, such as sulfur, calcium, and perhaps chlorine and silicon, are extremely unusual in

VISUAL SYMPTOMS ON DECIDUOUS FRUIT TREES *(Continued)*

deciduous fruit orchards. This probably is a result of their incidental application in routine sprays, their appearance in fertilizer, their general presence in adequate quantities in the soil, or their deposit from air-borne substances.

Courtesy of R. D. Dickey and G. H. Blackman, Florida Agri. Exp. Sta.

Figure 9. Zinc (Zn) deficiency in young Jewel peach tree. Characteristic symptoms of acute deficiency described as "Little-Leaf"—crinkling, rosette, defoliation and twig dieback.

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES

Fruits considered in this chapter under the heading of nuts are those generally grown in the temperate zone, namely, the almond, chestnut, filbert, pecan, tung, and walnut. Since the almond is so closely related to the peach, symptoms of deficiencies of the almond are not discussed separately from those of the peach. As far as possible, symptoms are described in such a way as to apply to all nut crops. Where this is not

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

possible, differences in symptom expression on the individual crops are emphasized.

Use of leaf symptoms to determine the nutritional needs of nut trees is not so general today as heretofore. Techniques of diagnosis through leaf analysis have been developed in the last 20 years which make it possible to determine the nutritional condition of many nut species, thus

Figure 10. Zinc (Zn) deficiency of Jewel peach leaves in Florida orchard. Note crinkling, waving and chlorosis of leaves at left. Leaf at right is normal.

forestalling the appearance of deficiency symptoms. Nevertheless, all growers do not avail themselves of this technical service, and nutritional deficiencies and unbalances often are allowed to develop to the extent that symptoms appear.

Leaf type varies widely among the species of trees included under the heading of nuts in this chapter. Nevertheless, symptoms of the deficiency of an essential nutrient generally are similar enough that the specific element involved can be determined by referring to the key to symptoms of fruit trees at the end of this chapter.

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

Definite leaf patterns typical of a deficiency of a specific nutrient do not develop until the element has been in short supply for some time. The tree generally has responded to the deficiency by reduced growth or yield before symptoms are apparent. However, reduced growth or yield can result from any unfavorable environmental condition, therefore these symptoms are not necessarily indicative of a nutrient deficiency.

NITROGEN (N) DEFICIENCY

Symptoms of nitrogen deficiency in general are similar in all crops. As the nitrogen supply decreases, the color of the leaves changes progressively from dark to light green. Since other nutrient deficiencies, as well as certain infectious diseases may induce yellowing of leaves, it is impossible to say at any particular stage of loss of green color that a definite deficiency of nitrogen is indicated. The symptom may develop at any time during the growing season, depending upon weather conditions and the level of available nitrogen in the soil. The leaves of severely deficient tung trees become yellow and may develop a bronze coloration on their under surfaces similar to that occurring on the leaves of zinc-deficient trees. In most nut trees, the areas of leaf blade adjacent to the larger veins retain their green color longer than the inter-veinal tissue.

If signs of nitrogen shortage develop very rapidly and are extremely severe, the older, basal shoot leaves may develop extreme symptoms while the younger leaves show varying degrees of loss of green color. In milder cases, leaves on the whole tree may gradually become lighter green. Severely deficient leaves may develop necrotic areas along their margins, and in pecans and walnuts the leaflets may drop from the rachis.

Reduced shoot growth and yield, and sometimes small and poorly filled nuts, result from a deficiency of nitrogen in the edible species. In tung, a reduction of nitrogen insufficient to induce leaf symptoms will result in a reduction in pistillate flower differentiation and a consequent reduction in the succeeding year's crop (plates 14 and 15).

PHOSPHORUS (P) DEFICIENCY

Although nut-tree species, especially tung, respond to phosphorus, the appearance of symptoms of phosphorus deficiency is almost unknown under orchard conditions. Symptoms, however, have been induced in both pecan and tung trees growing in sand cultures.

In pecans, new shoots on phosphorus hungry trees are very slender and the leaves are bright green. As the deficiency becomes more acute,

the old leaflets become dull green and later yellow-green in color. Some necrosis occurs between the secondary veins. The necrotic areas merge on the older leaflets and the affected leaflets drop from the rachis. This necrotic condition of the older leaflets develops while the younger leaflets still are unaffected. These symptoms vary somewhat between varieties.

Induced phosphorus deficiency in tung appears as reduced growth accompanied by the development of a dark, almost blue-green, color of the leaves. As the deficiency becomes more severe, the midribs and veins on the lower surfaces of the leaves and the petioles become reddish purple.

POTASSIUM (K) DEFICIENCY

The most typical symptom of advanced potassium deficiency generally is a marginal scorch. In tung, this is also typical of advanced magnesium deficiency. In most tree-nut species a chlorosis precedes the death of marginal leaf tissue. This chlorosis is typically more general than that described for magnesium deficiency. Often, the earliest symptom of potassium deficiency is a recurving of petioles and a drooping and rolling of leaf blades which give the affected tree an appearance of wilting though the leaves are completely turgid. When this deficiency is severe, premature defoliation may occur, generally beginning at the tips of the shoots. This is in contrast to earliest appearances of symptoms on the basal shoot leaves. In tung, fruit still clinging to leafless shoots is a typical symptom of severe potassium deficiency. At this stage of development in tung, potassium and magnesium deficiency symptoms are difficult to distinguish. In pecan, poor filling of the nuts results from potassium deficiency, and in both pecan and tung, low oil content of the fruit and predisposition to cold injury characterize potassium deficiency (plate 16 and figure 11).

Courtesy of U. S. Dept. of Agri., Bogalusa, La.

Figure 11. Potassium (K) deficiency of tung. Note inter-veinal and marginal necrosis.

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

MAGNESIUM (Mg) DEFICIENCY

Magnesium deficiency, in its later stages, is characterized by a marginal leaf scorch. The first symptoms are a lighter green color along the margins and between the secondary veins of the leaflets in pecans, and of the main leaf blade in tung. In pecan the whole tree may present a lighter green color. In tung, the affected portions of leaf blades take on a gray-green appearance. Early defoliation generally results, the leaf drop starting just below mid-shoot and progressing in both directions. In tung, even an experienced diagnostician may have difficulty distinguishing potassium from magnesium deficiency from symptoms alone. If the deficiency of magnesium is mild, symptoms may not appear until late in the fall and may progress no farther than the chlorotic stage (plates 17, 18).

CALCIUM (Ca) DEFICIENCY

Leaf symptoms of calcium deficiency have not been observed on any tree-nut species under orchard conditions. On some of the deep sandy soils of the southeastern coastal plain on which some tung is grown, this crop has responded to calcium as a plant nutrient. Where any symptoms have been associated with the condition which is corrected by calcium applications, they have been characterized by burning of leaf margins similar to that resulting from a deficiency of magnesium. Neither symptom correction nor improved yield, however, has resulted, in these cases, from applications of magnesium without calcium.

IRON (Fe) DEFICIENCY

As in practically all plants, iron deficiency in the nut species is characterized by inter-veinal chlorosis on the very youngest leaves. The area between the veins becomes light-green to almost white in striking contrast to the veins which remain green. Of all symptoms, those of iron deficiency are the most universally typical and, once observed, generally can be recognized on any plant on which they may appear (plate 20).

A chlorosis identical with that caused by a deficiency of iron may result from a number of conditions other than a lack of available iron in the soil. Among these are high soil pH (lime induced chlorosis), excess copper, excess phosphorus, and incipient calcium deficiency. If any of these conditions is responsible for the chlorosis, application of iron salts to the soil will not bring about recovery. The application of dilute solutions of soluble iron compounds to affected leaves may bring about

temporary greening but only by correction of the soil condition responsible can permanent recovery be obtained. Although iron chlorosis in nut trees may be easily recognized by the layman, the services of a plant physiologist are necessary to diagnose the underlying causes and recommend corrective measures (plate 20).

MANGANESE (Mn) DEFICIENCY

The symptoms of manganese deficiency already described for deciduous fruit trees apply to all nut species on which this deficiency has been

Courtesy of R. H. Sharpe, Florida Agricultural Experiment Station.

Figure 12. Mouse-ear of pecan caused by deficiency of manganese (Mn).

observed (figures 16 and 17), with the exception of the pecan. On pecan, the deficiency is characterized by a malformation described as "mouse-ear," or "little-leaf." A shortening of the mid-vein of the leaflets changes the tips of the leaflets from pointed to rounded and the leaflets become slightly wrinkled and more-or-less cupped. In severe cases, the entire leaf is much smaller than usual (plate 19 and figure 12).

ZINC (Zn) DEFICIENCY

Zinc deficiency symptoms are variously described as "rosette" in pecan, "yellows" or "little leaf" in walnut, "little leaf" in almond, and "bronzing" in tung. Zinc deficiency in pecan is indicated in its earliest stages by a

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

yellowish mottling of the leaves, particularly in the tops of the trees. As the deficiency advances, the leaflets become narrowed and crinkled, and later, reddish-brown areas or perforations develop between the veins. These symptoms also are typical of zinc deficiency on walnut and almond. In pecan, shortening of internodes resulting from checking of new growth causes the foliage to have a bunched appearance. The name of the disorder is derived from this characteristic. Though trees are rarely killed by rosette, severe dying back of the current year's growth may occur and the pruning effect of this die-back may cause the trees to leaf out earlier in the spring with larger-than-normal leaves. By late fall, when deficiency symptoms are at their worst, the trees may have a rusty or bronzed appearance.

Courtesy of U. S. Dept. of Agri., Bogalusa, La.

Figure 13. Zinc (Zn) deficient terminal shoot of tung. Note wavy margins on younger leaves, and ragged margins of older leaves due to loss of necrotic tissue.

In tung, zinc deficiency first appears as wavy margins of leaves, and as a malformation of the younger leaves in which one half of the leaf blade is smaller than the other. Such a leaf curves towards its smaller half, giving it a sickle shape. In severe cases, this uneven growth affects whole trees, causing them to develop a one-sided appearance. An inter-veinal chlorosis of an olive-green shade develops and, as the severity of the disease increases, the lower surfaces of the leaves take on a purplish-bronze cast from which the name "bronzing" is taken. In extreme cases, necrotic spots occur at random over entire leaf surfaces. In mature trees, symptoms usually do not appear until late summer. Zinc-deficient tung trees are very susceptible to cold damage (plates 21, 22 and figure 13).

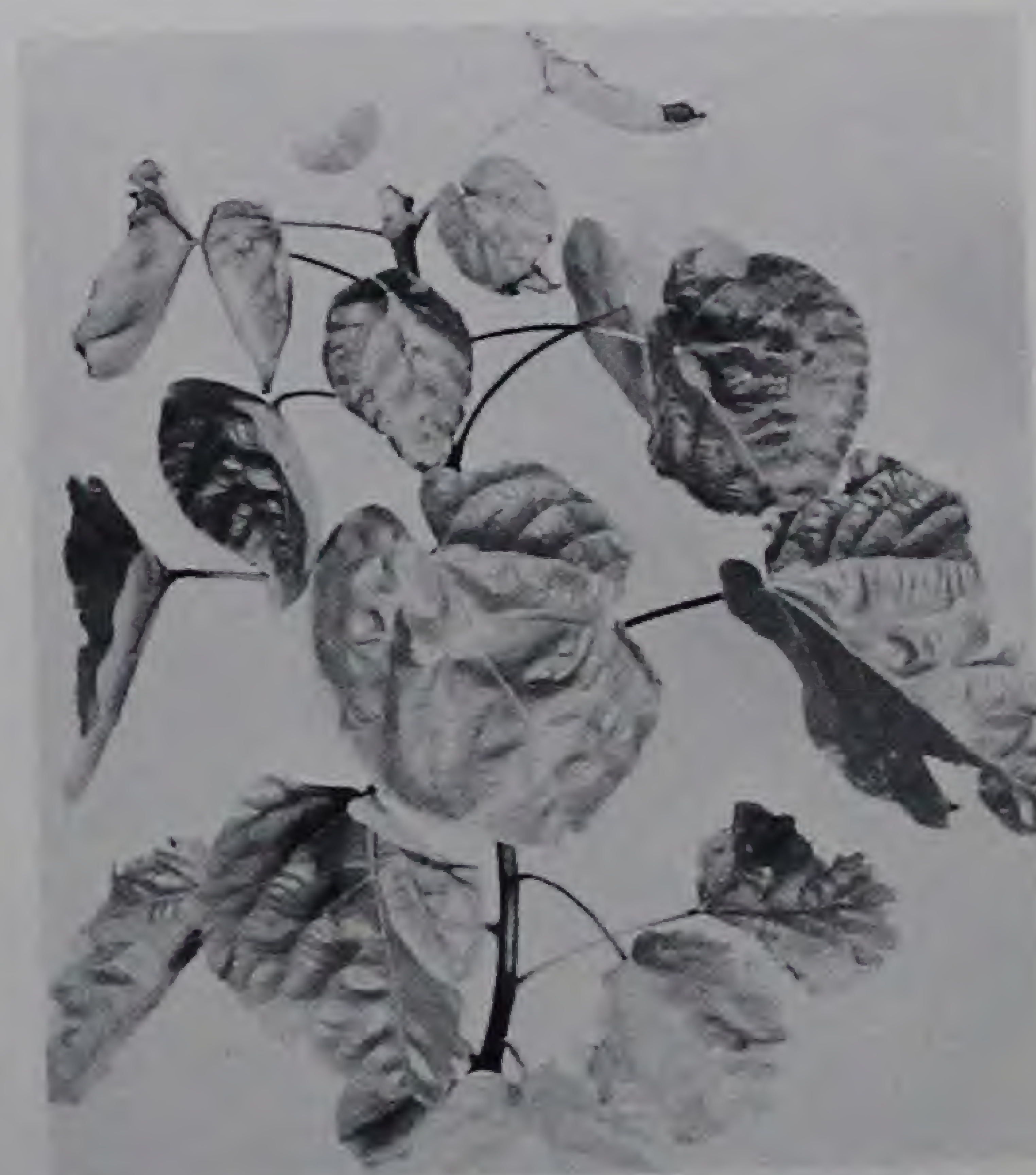
BORON (B) DEFICIENCY

Though symptoms of boron deficiency have been induced on pecan and tung in sand cultures, the disorder occurs under orchard conditions on walnut only. Signs of this deficiency are characterized by weak,

deformed twig growth having short internodes and deformed leaves. Shoots with rudimentary leaves, or leaves at the tips only, develop in the tops of trees. These sharply curved shoots may die during the following winter. It is from these dead, deformed shoots that the designation "snake head" is derived (figure 15).

COPPER (Cu) DEFICIENCY

Copper deficiency under orchard conditions has not been described on any nut species except tung and walnut. In tung the most characteristic symptom of copper deficiency is a "cupping" of the terminal leaves produced by the upward curling of their margins. Inter-veinal chlorosis and marginal burning of affected leaves usually is followed by necrotic spotting of the inter-veinal areas. Growth of unaffected portions of the leaves causes the dead marginal and inter-veinal tissue to fall away giving the leaves a ragged appearance. These leaves fall prematurely. The symptoms may develop at any time during the growing season and, sometimes, trees showing early symptoms may outgrow the disorder. In severe cases, the growing points of shoots may die, thus stimulating the growth of lateral buds (figure 14).



Courtesy of U. S. Dept. of Agri., Bogalusa, La.

Figure 14. Shoot from copper (Cu) deficient tung tree. Note upward cupping of terminal leaves, marginal cracking and inter-veinal puckering of older leaves.

In walnut, leaflets turn yellow and may show scorched areas late in the summer. These leaflets fall early. Dark brown dead areas appear on the bark of new shoots which may die back in late summer or early fall. The shells of nuts produced on affected trees have a chalky appearance and the kernels often are badly shriveled.

In both tung and walnut, copper and zinc deficiencies may be associated (plate 22).

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

Courtesy of C. J. Hanson, University of California, Davis, Calif.

Figure 15. Boron (B) deficiency on Persian walnut.

Courtesy of B. J. Dippenaar, Department of Agriculture, Pretoria, South Africa.

Figure 16. Manganese (Mn) deficiency on chestnut.

VISUAL SYMPTOMS ON DECIDUOUS NUT TREES *(Continued)*

Courtesy of E. F. Serr, University of California, Davis, Calif.

Figure 17. Manganese (Mn) deficiency on Persian walnut.

KEY TO NUTRIENT DEFICIENCY SYMPTOMS OF DECIDUOUS FRUIT AND NUTS

Specific nutrient deficiency symptoms on fruit and nut trees are most easily identified in the early or intermediate stages of development. Trees showing deficiencies usually have individual leaves in various stages of development of the symptoms. These should be studied carefully to become familiar with the manner in which the symptoms develop on an individual leaf as well as with the location on the tree where leaves are first and most severely affected.

The principal distinguishing characteristics used in this key apply to the early or intermediate stages of development on individual leaves, and to the positions on shoots or trees where symptoms usually first occur. On very severely affected plants or individual leaves, the symptoms for one element are frequently difficult to distinguish from those of another.

This key should be used only as a guide for preliminary identification, and final reference should be made to more detailed descriptions of symptoms in the text and for variations between species.

	Element Deficient
A. Symptoms generally appear first on older leaves. When youngest leaves are affected oldest leaves usually are falling.	
B. Marked "islands" of chlorosis or necrosis between main lateral leaf veins suggest a herring bone pattern. Leaf margins not affected in early stages. Sometimes V-shaped green areas appear with apexes toward leaf tips. Leaf size may not be affected	Magnesium
B. Leaf margins first affected, showing discoloration near upper or lower lateral edges; leaves laterally curling upward, smaller than normal. Marginal necrosis may be preceded by slight chlorosis. Marginal scorch	Potassium
A. Symptoms generally appear on youngest leaves.	
B. Young leaves chlorotic; veins remain green.	
C. Internodes markedly shortened near tip of shoot producing rosettes of small chloratic leaves. Older leaves may appear bronze and fall easily........	Zinc
C. Internodes not markedly shortened near tip. Fine lace-like network of leaf veins green. Youngest expanding leaf may be devoid of green color. Leaves acquire some green color with increasing age	Iron
C. Tip leaves chlorotic, main veins green, shoot tips frequently die back and new shoots grow out from lower buds producing dieback and witches'-broom	Copper
B. Young leaves not chlorotic or only slightly so.	
C. Young leaves may be curved boatlike; shoot tips may be curved; terminal buds aborted and new shoots die back........	Boron
C. Midribs of leaflets shortened, tips rounded, wrinkled, and cupped	Molybdenum
A. Symptoms generally appear on any part or all of plant.	
B. Leaves small, uniformly less green; reduced growth.	
C. Leaf petioles, lower side of main veins and young shoots show purple pigmentation during early stages of growth. This pigmentation may disappear later in season and leaf color improve........	Phosphorus
C. No marked pigmentation. Pale color may become worse with increasing leaf age........	Nitrogen

	Element Deficient
B. No marked reduction in leaf size. Pale green color between main veins with large lateral veins showing broad band of green. Very fine veins not distinguished. Increasing in severity late in season. Young expanding leaves usually do not show symptoms. Chlorotic pattern somewhat between that of magnesium and that of iron....	Manganese
A. Symptoms principally on fruit.	
B. Young fruit show corky lesions. Frequently internal necrotic spots in fruit or internal cork....................................	Boron

Note: Molybdenum deficiency is not common enough on deciduous fruit for the symptoms to be well defined.

Calcium deficiency is usually not clear-cut under field conditions. When soil conditions are such as to produce calcium deficiency, other deficiencies are usually so acute its identity becomes obscure and of secondary importance. Normally the liming of soils for physical conditioning, pH control and its effect on the availability of other nutrients is necessary before calcium becomes deficient as a nutrient. Thus, although the symptoms can be readily produced in artificial culture their recognition in the field is relatively unimportant.

CORRECTIVE MEASURES

Once a nutrient deficiency is recognized, the obvious corrective measure is to provide this nutrient to the tree. Unfortunately, identification of a symptom does not tell how much nutrient is needed, but the degree of severity of the symptom may be used as a guide. Since efficiency of fertilization varies greatly with many soil and climatic factors, the quantity necessary to achieve the desired result can be determined only by trial or making use of local experience.

Generally speaking, the following rules apply:

The major nutrients, nitrogen, phosphorus, potassium, calcium, and magnesium, being required in relatively large quantities by most plants usually are most effectively applied as fertilizer to the soil surface. Of these nitrogen and potassium are most rapid in action and phosphorus usually is slowest because of differences in rates at which they move down through the soil.

Nitrogen is most easily lost from the soil and usually is required annually in fertilizer to maintain production. Usually, one application will correct a deficiency of potassium and an application every three to five years will maintain the supply, except perhaps on very light soils. If adequate supplies of phosphorus, calcium, and magnesium are insured at planting time, these quantities probably will suffice for the life of the orchard. On established orchards, three to five years may elapse after surface applications of materials carrying these nutrients before appreciable quantities are absorbed by the trees.

The minor nutrients, iron, manganese, zinc, copper, and boron, are required in very minute quantities and frequently are applied as foliage sprays for most rapid response. One or 2 pounds of the appropriate salt per 100 gallons of water usually suffice. However, the treatment may have to be repeated annually for several years before a maintenance cycle is established. Some of these "micronutrients" are tied up in many soils and are difficult to get into the tree by soil applications. However, there is some evidence that they more readily get through this barrier when biologically incorporated in plant tissue. Thus, foliage spraying provides a rapid but temporary correction. Eventually through the return of leaves to the soil together with cover crop residue, a maintenance cycle of "organically chelated" forms of these elements may be established.

SELECTED REFERENCES

Any selected list of references to the literature on this subject would be incomplete and a comprehensive bibliography is beyond the scope of this book. Comprehensive lists of references are contained in the works listed:

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Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate. 1. Nitrogen (N), deficiency on golden Delicious apple. Note uniform pale color, smaller leaves and short shoot growth.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 2. Nitrogen (N) deficiency on Halehaven peach (left), healthy (right).

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 3. Potash (K) deficiency on Golden Delicious apple. Note increasing severity of marginal scorch toward base of shoots, smaller leaves and reduced growth.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 4. Potash (K) deficiency on Halehaven peach. Note increased severity of symptoms toward base of shoot, upward curling of leaves, smaller leaves and reduced growth.

Courtesy of American Potash Institute

Plate 5. Potash (K) deficiency on pear. Potash treated trees (left); note small leaves, marked upward curling and the brown etched appearance of the lower leaf surface at the lateral margins (right).

Courtesy of American Potash Institute

Plate 6. Potash (K) deficiency on French prune. Green leaf at left and top row of fruit are from potash treated tree. Note small leaves, irregular marginal scorch and small fruit on deficient prune.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 7. Potash (K) deficiency on Montmorency cherry. Right: Note small leaves, short growth, upward curling of leaves, and the etched browning of the lower surfaces near the lateral margins.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

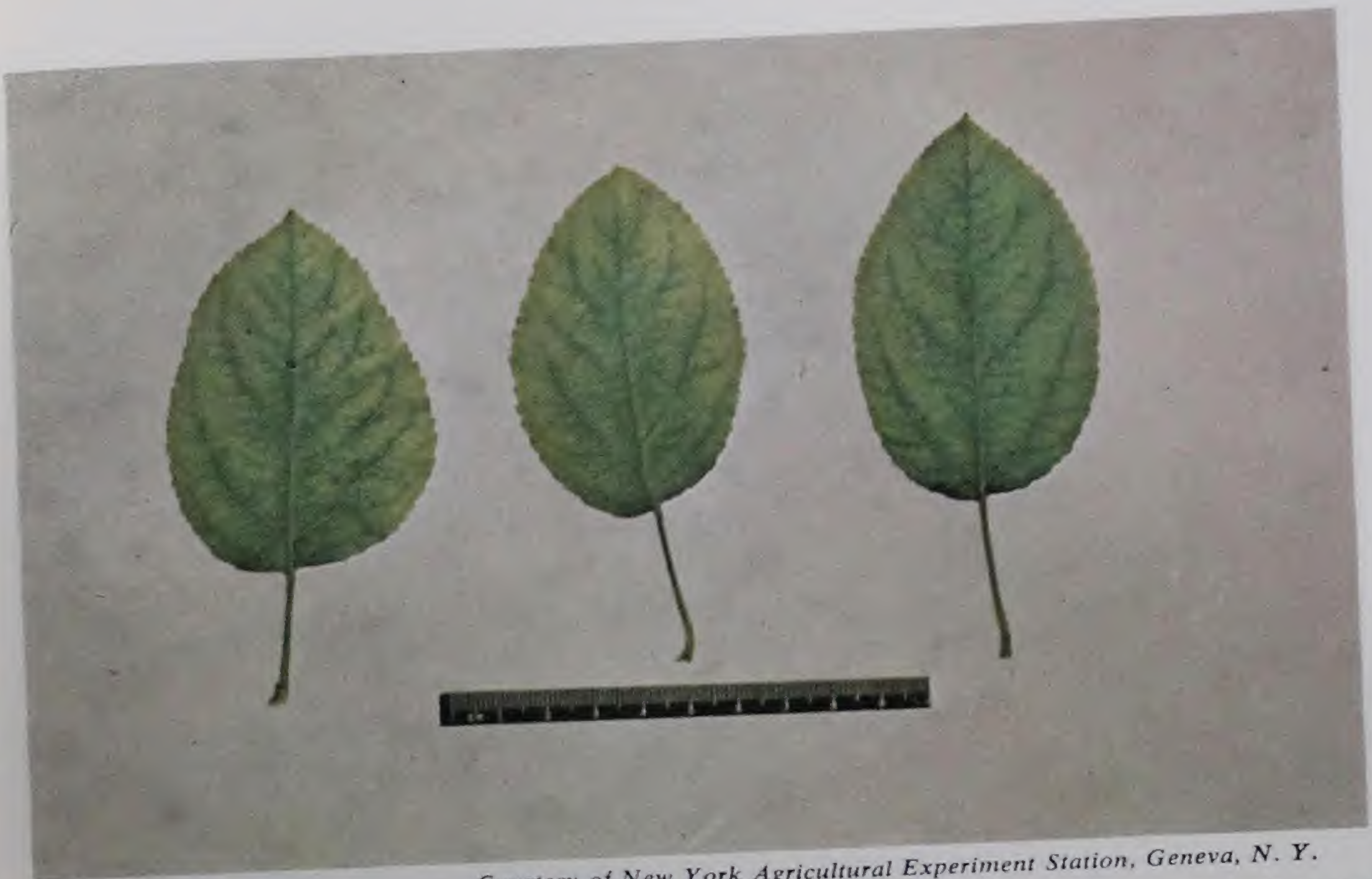
Plate 8. Magnesium (Mg) deficiency on McIntosh apple. Note pattern of inter-veinal chlorosis and increased severity on older leaves. Severely affected leaves defoliate easily.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 9. Magnesium (Mg) deficiency on Halehaven peach. Note herringbone pattern of chlorosis and necrosis developing between lateral veins between the midrib and the leaf margin.

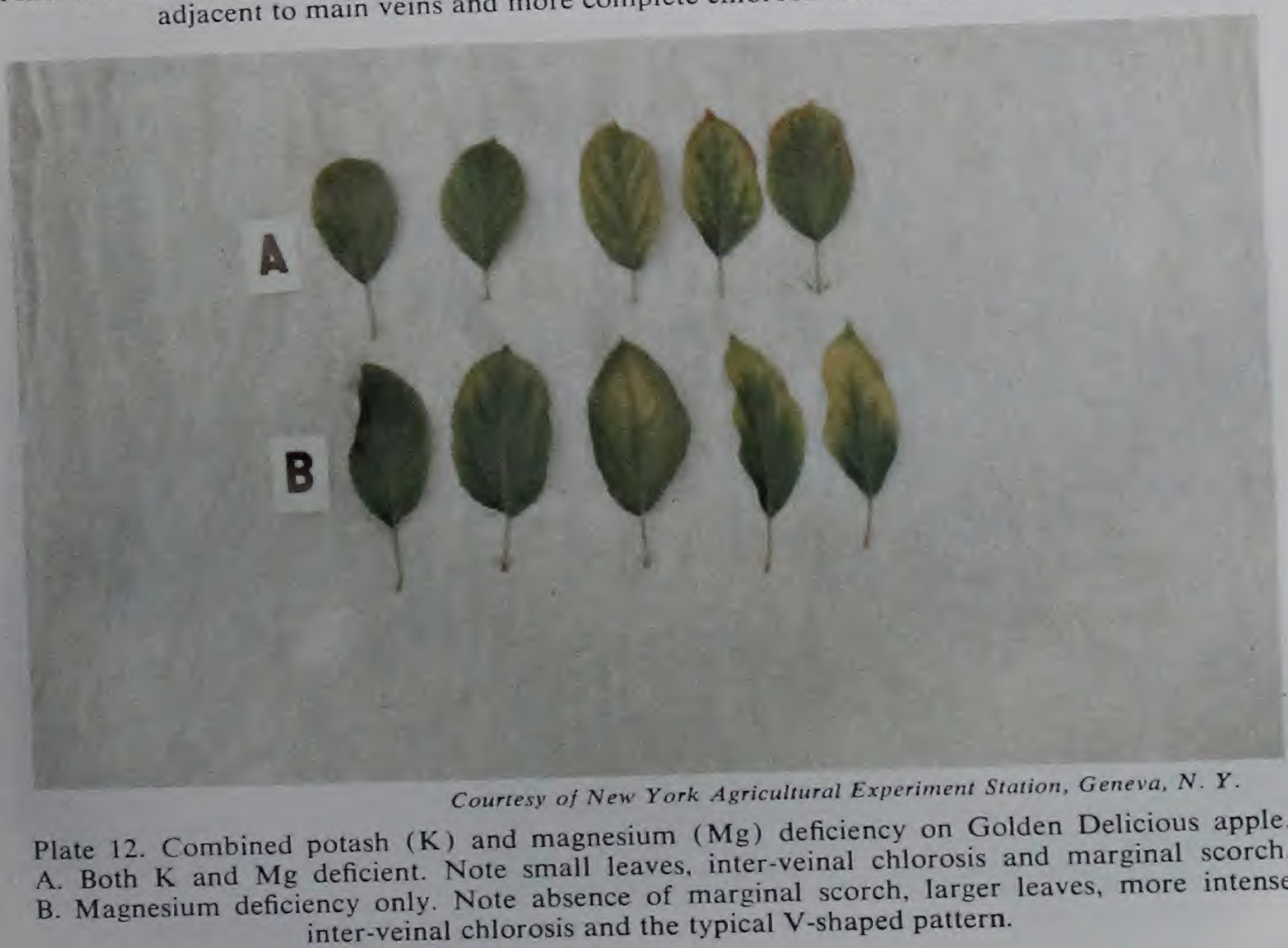
Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 10. Magnesium (Mg) deficiency on Halehaven peach. Left to right—tip to basal leaves on shoot. Note V-pattern of green, inter-veinal chlorosis followed by necrosis.



Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 11. Manganese (Mn) deficiency on McIntosh apple. Mature leaves. Note area of green adjacent to main veins and more complete chlorosis near margin of leaf.



Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 12. Combined potash (K) and magnesium (Mg) deficiency on Golden Delicious apple. A. Both K and Mg deficient. Note small leaves, inter-veinal chlorosis and marginal scorch. B. Magnesium deficiency only. Note absence of marginal scorch, larger leaves, more intense inter-veinal chlorosis and the typical V-shaped pattern.

Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Plate 13. Combined potash (K) and nitrogen (N) deficiencies on Golden Delicious apple. Upper row: Nitrogen deficient. Left—from tree with adequate potash; right—(4 leaves) from tree deficient in potassium; lower row: Nitrogen adequate. Left—from tree with adequate potassium; right—(4 leaves) from high nitrogen tree, deficient in potassium. Note the lesser marginal scorch and more chlorosis on potash deficient leaves with high nitrogen supply.

Courtesy of A. C. Gossard, U. S. Dept. of Agri., Meridian, Miss.

Plate 14. Nitrogen (N) deficient pecan tree. Note the yellow-green color of the deficient tree in contrast to the dark green nitrogen-sufficient trees in the background.

Courtesy of U. S. Department of Agriculture, Bogalusa, La.

Plate 15. Nitrogen (N) deficient tung tree (left) in comparison with tree receiving adequate nitrogen (right). These symptoms produced in sand cultures.

Courtesy of A. C. Gossard, U. S. Department of Agriculture, Meridian, Miss.

Plate 16. Pecan leaves showing leaf scorch due to potassium (K) deficiency.

Courtesy of A. C. Gossard, U. S. Department of Agriculture, Meridian, Miss.

Plate 17. Pecan leaf showing marginal and inter-veinal chlorosis due to deficiency of magnesium (Mg).

Courtesy of U. S. Department of Agriculture, Bogalusa, La.

Plate 18. Magnesium (Mg) deficient shoot of tung.

Courtesy of U. S. Department of Agriculture, Bogalusa, La.

Plate 19. Manganese (Mn) chlorosis of tung. Compare this symptom with that of iron deficiency (plate 20).

Courtesy of U. S. Department of Agriculture, Bogalusa, La.

Plate 20. Iron (Fe) chlorosis of tung. This symptom indicates a lack of functional iron in the leaf but does not necessarily indicate a lack of iron in the soil. In this case, iron deficiency was induced by a lack of calcium.

Courtesy of A. C. Gossard, U. S. Department of Agriculture, Meridian, Miss.

Plate 21. Pecan shoot showing rosetted terminal leaves resulting from a deficiency of Zinc (Zn).

Courtesy of U. S. Department of Agriculture, Bogalusa, La.

Plate 22. Combined Zinc (Zn) and Copper (Cu) deficiency of tung.

Chapter X

Nutrient Deficiencies in Small Fruits and Grapes

By Carter R. Smith, Nelson Shaulis and James A. Cook *

NUTRIENT deficiency symptoms observed in strawberries, blueberries, brambles (genus Rubus) and grapes are described in this chapter in some detail. Some economic loss already will have resulted by the time deficiency symptoms are noticeable in these crops and every effort should be made to prevent their occurrence. This is not always possible due to environment, soils, and management programs; so, early recognition and correction of hunger signs in these plants is important.

Many similarities are found in the appearance of symptoms of the same nutrient deficiency regardless of the crop, and accurate diagnosis depends on broad knowledge of affected species. For instance, in the East, Jerseybelle strawberry plants inherently have a darker green foliage than Dixieland plants. In the Pacific Northwest, Marshall strawberry plants are darker green in color than other strawberry plants in that region. Since nitrogen deficiency tends to result in lighter green or yellowish-green leaves, knowledge of the healthy foliage color of a variety is important. Pathogenic diseases also may cause confusion. Symptoms of a certain virus disease, known as "mosaic," of blueberries, fortunately not widespread, can be confused with signs of magnesium deficiency.

Once a deficiency has been corrected a management program should be followed that will prevent it from reappearing. Soil and foliar leaf analysis can be used to check on the effectiveness of such a program. Generally, soil analysis is used with strawberries. The strawberry is a shallow rooted plant and a good soil sample usually represents the soil mass invaded by the roots. Foliar (leaf blade) analysis or petiole (leaf

* Carter R. Smith, Associate Professor of Pomology, Rutgers University, prepared the small fruits portion of this chapter and Nelson Shaulis, Professor of Pomology, New York Agricultural Experiment Station, Geneva, and James A. Cook, Associate Professor of Viticulture, University of California, Davis, prepared the material on grapes.

stem) analysis is used to assay the nutrient status of grapes, because grape roots penetrate to soil layers not included in ordinary soil samples. Not enough information is available to establish reliable judgment concerning the use of soil or foliar analysis in diagnosing nutrient problems in blueberries and brambles. Nevertheless, chemical analysis of soils and foliage are valuable tools of scientists and both can be used in approaching nutrient problems through research.

STRAWBERRIES

Strawberries are grown on a wide variety of soil types and under many different climatic regimes. It is a tribute to the excellent management of those who grow strawberries that nutrient deficiency problems are not so serious as with some other crops. This does not mean that when difficulties occur they are not troublesome, but because of high production costs, strawberry growers, through fertilizer programs, try to avoid nutritional problems. The strawberry plant is relatively shallow rooted and most commercial growers provide their plantings with irrigation. This allows the grower to manage his fertilizer program to an extent unknown in some other crops where rooting is deep and where rainfall is the only means of carrying fertilizer to the roots.

Strawberry growers also are prone to use their best soils and sites for the production of this crop; returns per acre make the use of the best situations worthwhile. But even under these conditions nutrient deficiencies sometimes occur and their early detection and correction is important to protect the sizeable investments that usually are involved.

NITROGEN (N) DEFICIENCY

Nitrogen deficiency is the only plant nutrient shortage that can be said to affect strawberries in every region where they are grown. Lineberry and Burkhart (8) report that new leaves of affected plants become yellowish-green or lighter green while other foliage develops a red color at the leaf serrations. Loss of vigor also is associated with lack of nitrogen. In severe cases the foliage becomes distinctly yellow, the older leaves turning red. As nitrogen deficiency advances the older leaves become light yellow and small necrotic dead spots appear. Advanced cases of nitrogen shortage rarely are found in the field because supplementary applications of nitrogen fertilizer quickly correct such deficiencies when irrigation or rain moves this nutrient into root zone.

PHOSPHORUS (P) DEFICIENCY

A deficiency of phosphorus in strawberries sometimes is very difficult to detect in the field if the observer depends upon visual symptoms alone. Early symptoms described by Lineberry et al (9) are a deeper green or bluish-green color of the foliage. Lineberry (9) also points out that young leaves are small, thin, dark green, and show poor development. Looking at a field of strawberries in the early stages of phosphorus deficiency, the grower will see very little to cause him concern except poor development. The darker green shade does not take on significance until poor development is noticeable. In later stages of this deficiency a bronze or purple coloration develops in strawberry leaves.

Correction of this deficiency in the short time allowed by a maturing crop is difficult because of phosphorus fixation in the soil. Every effort should be made to prevent its appearance by preplant applications of phosphorus fertilizers where needed (plate 1).

POTASSIUM (K) DEFICIENCY

Potassium deficiency in strawberries as observed by Lineberry and Burkhart (8) gives rise to a marginal necrosis which causes leaflets to gradually roll upward and inward. On the Blakemore variety, the inter-veinal tissue of the younger leaves of potassium hungry strawberry plants became light green to yellow, but on the Klondike variety the petioles just below the leaflets became necrotic and the midribs of the leaflets became purple. Iwakiri and Scott (6) who used the Temple variety in potassium deficiency tests observed a marginal chlorosis on fully expanded leaves followed by inter-veinal chlorosis (plate 2).

MAGNESIUM (Mg) DEFICIENCY

Deficiency symptoms for this element do not often appear in the field. Lineberry and Burkhart (8) report that under controlled conditions a downward and inward rolling of yellowish-green leaf margins occurs. In advanced stages they observed a yellowish-orange inter-veinal coloration. Iwakiri and Scott (6) working with sand cultures, report that earliest symptoms of magnesium deficiency appear in an inter-veinal chlorosis of the older leaves. In later stages they observed bands of reddish-brown coloration around the edges of the leaves, some leaflets having discolored areas near their margins (plate 3).

CALCIUM (Ca) DEFICIENCY

Calcium deficiency, as such, is not known under field conditions. Calcium in the form of lime is used for soil pH control. Sometimes pH

problems and calcium deficiency are confused. Amounts of calcium used for pH control usually are more than adequate for the nutrient requirements of strawberry plants. When grown at low calcium levels under sand culture strawberries were observed by both Lineberry and Burkhart (8) and Iwakiri and Scott (6) to suffer from tip burn of young leaves. Although tip burn is associated with a low level of calcium in the soil, it also may result from low levels of other cations and may not be a reliable symptom of calcium deficiency. Tip burn of strawberries in the field is evidence of a nutrient problem; hence calcium, magnesium, and potassium levels of the soil should be checked.

Under sand culture conditions, calcium deficiency has caused leaves of strawberry plants to lose their luster and to suffer from inter-veinal chlorosis and slight marginal necrosis.

BORON (B) DEFICIENCY

Boron deficiency symptoms in a strawberry field can be dramatic because they cause dwarfing and distortion of plants and fruits. The problem of boron deficiency should be approached with great care, because the strawberry plant is rated as boron sensitive and toxicity from an excess of this element can be as serious as deficiency. Where boron is suspected of creating a problem, growers should consult their local agricultural agents or qualified personnel at agricultural experiment stations. In general, when strawberries follow a crop fertilized with boron they will not require added amounts (plate 4).

IRON (Fe) DEFICIENCY

Iron deficiency is a problem in strawberries when they are grown on alkaline soils. The leaves become chlorotic and the plants are stunted. Repeated iron sulfate sprays or applications of iron chelates to the soil will relieve the deficiency. Fungicides containing iron are reported to have produced similar results. Strawberries grown on good agricultural soils within the pH range of 5.5 to 6.5 should not suffer from want of iron.

COPPER (Cu), ZINC (Zn), AND MANGANESE (Mn) DEFICIENCIES

Deficiencies of these elements are rarely detected in strawberry plants under field conditions. Copper deficiency causes the younger leaves to become pale green with red areas between the veins. This deficiency produces a pronounced red discoloration in stems and leaf petioles. Zinc deficiency, an affliction which appears similar to copper deficiency in

strawberry plants, does not produce the red discoloration of stems and petioles but, to a degree, causes the leaflets to be narrower than normal. Manganese deficiency also produces leaf symptoms similar to those of copper shortage in strawberry plants but causes development of small crinkled leaves. This deficiency is apt to occur on soils of high pH or where too much lime has been applied.

BLUEBERRIES

The cultivated highbush blueberry *Vaccinium corymbosum L.* requires a soil having low pH. This is typical of ericaceous heath plants but quite different from most other agricultural crops. Low soil pH sometimes causes problems in mineral nutrition leading to expression of deficiency symptoms. It also makes correction of these deficiencies difficult when blueberries are grown on soils that do not, under natural conditions, meet this low pH requirement.

NITROGEN (N) DEFICIENCY

Nitrogen deficiency in blueberries is expressed in reduced growth, a symptom common to many deficiencies, the basal leaves turning yellowish-green. As the symptoms become more severe, entire plants take on a yellowish-green color and growth is definitely stunted. Amling (1) reports that shoots arising from the base of nitrogen deficient plants have a distinct pink coloration. These shoots quickly changed to light green when growth stopped. With extreme nitrogen deficiency Amling also noted necrotic spots over the entire surfaces of basal leaves (plate 9).

Cain (2) suggests that ammonium nitrogen is preferred to nitrate nitrogen in the nutrition of blueberries and ammonium nitrogen may be associated with iron nutrition in the plants.

PHOSPHORUS (P) DEFICIENCY

A dark green or purplish-green color of blueberry foliage is associated with phosphorus deficiency, and the leaves take on a leathery texture.

Amling (1) reports that the darker green or purplish-green color is not confined to mature leaves but also is exhibited by growing tips. Light affected expression of symptoms in his work; high light intensity resulted in purple coloration and shading caused it to disappear (plates 5, 6, 10).

POTASSIUM (K) DEFICIENCY

A deficiency of potassium in the growing medium of blueberries results in necrotic spotting and marginal scorching of the leaves. These

symptoms appear first on the older foliage. Kramer and Schrader (7) point out that symptom expression of potassium deficiency is complicated by periodic "abortion" of terminal growing points. They feel this is the reason why severe deficiency symptoms, already described, appeared first on the older leaves of deficient plants while interveinal chlorosis appeared later. The inter-veinal chlorosis appeared on new growth arising from auxiliary buds stimulated to grow by the death of terminal buds.

Amling (1) working with blueberries grown in sand cultures supplied with nutrient solutions did not observe potassium deficiency symptoms in the foliage of plants until six weeks after treatments were initiated. During the first four weeks after treatments started, the plants were supplied 26 parts per million of potassium and then no potassium was included in the nutrient solution. Kramer and Schrader (7) developed foliar deficiency symptoms of potassium much sooner in their studies with blueberries (plates 5, 6).

CALCIUM (Ca) DEFICIENCY

Literature concerned with foliage deficiency symptoms of calcium in blueberries seems very inconclusive. Kramer and Schrader (7) report symptoms similar to those induced by potassium deficiency, and Amling (1) reports a slight yellowish-green blotchiness of terminal leaves. In a different experiment he noted a marginal chlorosis of the tip leaves and a tendency toward rosetting.

MAGNESIUM (Mg) DEFICIENCY

Of all the nutrient problems of blueberries, magnesium deficiency appears to be second only to that of nitrogen and possibly is more troublesome. Nitrogen deficiency is rather easy to correct but magnesium deficiency offers some special problems.

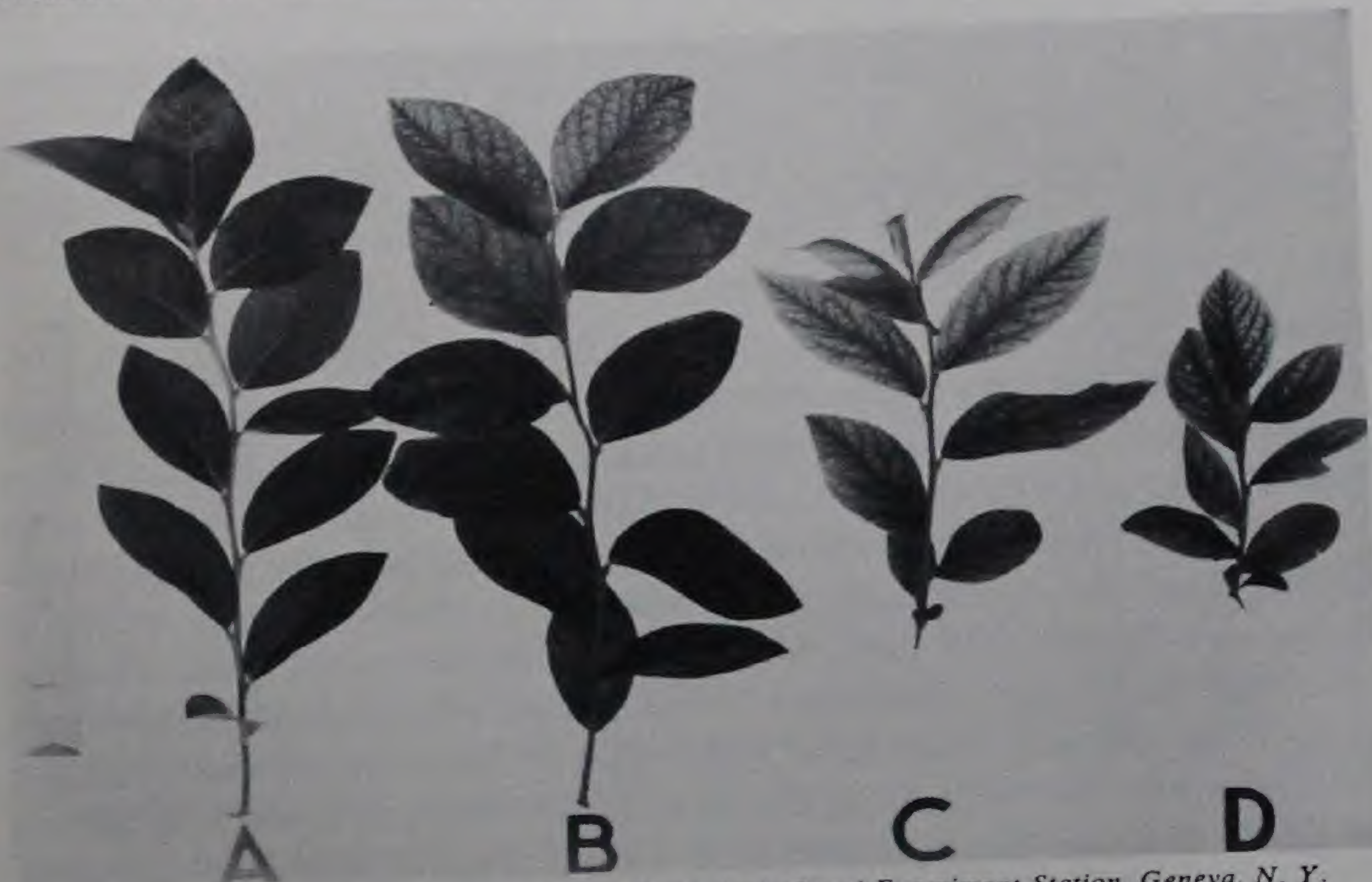
Magnesium deficiency in blueberries can be recognized by the bright red leaves of afflicted plants. Coloration of their submarginal interveinal areas is in strong contrast to the green which prevails along their midribs. These green areas take on a "Christmas tree" form. Other symptoms occur, such as necrotic (dead) spots and shades of yellow or brown in place of red, but for the most part, in the field, the red coloration and "Christmas tree" green areas of leaves are characteristic symptoms of this deficiency.

It can be corrected by applications of magnesium sulfate. In New Jersey, recommendations have been made that this chemical be added to the regular fertilizer mixture which is applied annually to blueberry

plantings. In other agricultural crops, dolomitic limestone is used to correct magnesium deficiencies, but this method is not suitable for blueberries because a low soil pH must be maintained (plates 5, 6, 8, 11).

BORON (B) DEFICIENCY

Boron deficiency in blueberries is recognized by a bluish color of terminal leaves followed by a mottled spotting of young growth. Kramer



Courtesy of New York Agricultural Experiment Station, Geneva, N. Y.

Figure 1. Iron deficiency on Jersey blueberry. Note chlorosis of youngest leaves. Older leaves become green in less severe cases (A and B); shoot growth is reduced when deficiency is severe (C and D).

and Schrader (7) also noted some leaf distortion but this does not always appear. Amling (1) reported that tip leaves ceased to enlarge but made no comment on leaf distortion.

IRON (Fe) DEFICIENCY

An inter-veinal chlorosis of the younger leaves may indicate iron deficiency in blueberries in the field. This disturbance is not necessarily related to low amounts of iron in the soil, but often occurs in blueberry plants growing on mineral soils where the pH is higher than optimum. The disorder can be corrected by soil applications of iron chelates or repeated spraying of the foilage with iron sulfate. Iron chelates are com-

plex organic compounds that carry iron in a readily available form (plates 7, 12 and figure 1).

SULFUR (S) DEFICIENCY

Under ordinary conditions sulfur deficiency is not expected to appear in geographic regions close to industries or large populations. In these areas the atmosphere usually is supplied with rather large quantities of sulfur, and enough is washed down into the soil with rain to prevent the appearance of sulfur deficiency in plants. Also, use of 20 percent, single strength, super-phosphate in fertilizer supplies sulfur to cultivated crops. Kramer and Schrader (7), working in sand culture, found sulfur deficiency symptoms in blueberries to resemble those of nitrogen deficiency but the yellow color was more bleached in appearance and turned to faint pink in later stages.

BRAMBLES

The information presented in this section applies to members of the genus *Rubus* that are grown commercially, such as red, black, and purple raspberries, and blackberries. All brambles are biennial in nature. The first year they produce canes called "primocanes" and, in general, these do not bear fruit. Some varieties produce fruit on terminal branches at the end of the first year. The second year, the same canes produce fruit and are called "floricanes." The primocanes should be observed closely for nutrient disorders. They must be kept in the best nutrient condition, because any restriction in growth is likely to cause a reduction in dormant flower buds produced in the fall; thus, a decline in fruit production the following year may occur.

NITROGEN (N) DEFICIENCY

Nitrogen deficiency symptoms in brambles are similar to those observed in other crops. A chlorosis of the older leaves which progressively involves the younger leaves, along with a reduction of growth or loss of vigor, are signs to watch for in the field. Loss of vigor alone is not a reliable indication of nitrogen deficiency. Virus diseases are important in causing economic damage to bramble plantings and these diseases also cause a reduction in growth. Nitrogen deficiency symptoms in advanced stages are indicated by premature leaf abscission (dropping) and the development of red coloration in the leaves.

PHOSPHORUS (P) DEFICIENCY

Hagler (5) noted that a deficiency of phosphorus caused the leaves of dewberries to become dark green to purple. These same symptoms

were observed by Ranig and Vandecaveye (10) on red raspberry leaves when phosphorus was deficient. They also noted a reduction in leaf size and a curling and stiffening of the leaves.

POTASSIUM (K) DEFICIENCY

Ranig and Vandecaveye (10) observed that the first symptom of potassium deficiency in brambles was a reddish-brown pigmentation of the inter-veinal mesophyll ridges of mature leaves. Later, the older leaves took on a bronzed appearance and areas of dead tissue developed. Severe potassium deficiency caused the leaves to curl or roll and to become stiff. Marginal scorch and necrosis, which can involve half of the area of affected leaves, also are associated with severe deficiencies of potassium.

CALCIUM (Ca) DEFICIENCY

Calcium deficiency never has been reported in brambles under field conditions. Lime applied for pH control rules out the possibility of calcium deficiency in most crops. Application of lime brings about a favorable situation for the development of crown gall of brambles and, in general, lime is not applied to bramble fields. Calcium deficiency could be a field problem and the symptoms observed by Ranig and Vandecaveye (10), working with red raspberries in solution culture, may help in diagnosing the problem. They found reduction in leaf size with leaf hardening and curling to be above-ground symptoms, while at the same time, death of root tips occurred. Areas immediately behind dead root tips were swollen with growth of new rootlets forming compact masses Hagler (5), working with calcium deficient dewberry plants, found marginal and inter-veinal chlorosis of the leaves, the young leaves and terminal portions of canes being affected.

GRAPES

Commercial production of grapes in the United States is almost completely restricted to three species: *Vitis labrusca*, *V. rotundifolia*, and *V. vinifera*. Some overlapping of distribution prevails because of differential adaptations to climatic conditions, but commercial plantings of each species are restricted in general to separate geographical areas within the United States. Thus, hybrids marked by *V. labrusca*, with the Concord variety as an example, cover the Northeast as far south as South Carolina, are spread through the Midwest along the southern shore of Lake Erie, and are found in parts of Washington and Oregon in the Pacific Northwest. *V. rotundifolia* dominates plantings in the

southeastern part of the country, from Virginia to the Lower Mississippi Valley. Over 90 percent of the acreage of *V. vinifera*, the most important and widely planted species in the world, is concentrated within the state of California with the remaining acreage mostly in Arizona.

Although these three grape species differ greatly from each other, particularly in nature of fruit, present knowledge indicates that they are quite similar insofar as visual symptoms of nutrient deficiencies which may develop are concerned. Therefore, for the purposes of diagnosis, the discussions which follow apply to all three species except for a few noted variations.

The mineral nutrition status of a plant from the standpoint of a particular element may be described as falling into one of four classifications: (1) The plant concerned may contain a much higher than necessary amount of the particular nutrient. If the plant is quite tolerant toward the element, this status is referred to as luxury consumption; if not, the high amount may be toxic and detrimental to its healthy growth. (2) The plant may contain an amount of the nutrient within the wide limits of its optimum or desirable range. Of course, in this case it will show no signs of shortage. (3) The plant may contain the nutrient at a level just below its optimum range so that its performance is limited. Abnormal symptoms will be discernible to careful observers who know the signs of the deficiency as well as the time and place at which it first may be expected. (4) The plant may contain the nutrient so low that abnormal symptoms, characteristic of the particular deficiency, may develop generally in some or all of its parts.

Early detection of stage 2 is highly desirable and much effort, time, and money are being spent to develop better methods for such diagnosis. However, stage 4, the category in which obvious visual symptoms develop, is of primary concern in the present discussion. Ability in identifying stage 4 leads to competence in recognizing stage 3, a more important accomplishment. By the time visual symptoms appear generally in a vineyard, considerable crop loss is likely to be involved except under unusual circumstances. The reason why ability to recognize symptoms of nutrient hunger, the sooner the better, is of so much practical importance is the possibility of forestalling appreciable crop loss through application of corrective elements.

Many hunger signs are distinct and can be recognized on sight by growers having a little experience. Other indications of nutrient shortage are less distinct and growers may need help in their identification. Incipient or first stages of visual symptoms may be so questionable that

diagnosis should be confirmed by a specially trained scientist or by chemical analysis of the foliage, preferably the leaf petioles in the case of grapes. A few nutrient deficiency symptoms are indistinct and may be misleading because of similarity to damage caused by disease infection or injury due to sprays, drought, heat, or insects. When such signs of distress appear, even well trained observers may require supplementary information on vineyard location and history, soil type, rootstock involved, and general vine-to-vine distribution of symptoms in order to avoid error in diagnosis.

Problems of diagnosis of hunger signs in plants are greatly reduced by knowledge of those nutrients which are most likely to be deficient within a given region. Calcium deficiency in grapes has not been reported. Except for a report by Randolph of a fertilizer trial on grapes of the Carmen variety in Texas, no evidence of clearcut response of grapes to phosphorus in any part of the United States has been published. In the Great Lakes area, the most common deficiencies in grapes are for nitrogen, potassium, magnesium, and manganese. In Washington and Oregon, the Concord variety may show need for nitrogen, iron, or zinc. The most common deficiencies of *V. rotundifolia* varieties in the Southeast are for nitrogen and magnesium, shortages of potassium and boron occasionally being suspected. In California, deficiencies of importance are restricted to nitrogen, potassium, zinc, and boron.

Within these general regions, the nature of local soil conditions from the standpoints of texture, depth, and drainage are aids in diagnoses. For example, deficiency of manganese or iron in grapes is more likely where erosion is minor, drainage is imperfect, and soil pH is nearly neutral; nitrogen deficiency is more likely where erosion is severe. Mild deficiencies sometimes are demonstrated in the pre-bloom occurrence of hunger signs for nitrogen or iron which may be less clear at harvest time; hunger signs for potassium or magnesium occasionally are most advanced and recognizable at harvest. If such symptoms are seen earlier, immediate corrective fertilizer applications are in order.

Deficiencies are expressed both in the leaves and in other parts of grape plants. If, upon recognizing a specific type of discoloration or chlorosis, as shown in the descriptive photos, the observer notes the position of the affected leaves and whether other portions of the vine show indications of abnormal development, his diagnosis may be much more accurate.

Since a slowing of growth probably already has occurred by the time visual hunger symptoms are generally apparent, the sooner the signs

are detected and recognized, the more quickly the deficiency may be remedied and the less the loss of crop. Grape growers always should be on the alert for any variation in plant size, leaf size, or shape, stunting of shoot growth, cluster size and berry set, as well as any unusual leaf coloration or chlorosis in their vineyards.

When vines having abnormal appearance are located, the grower first should determine whether or not the symptoms can be explained by some condition other than mineral nutrition. Magnesium deficiency and potassium deficiency symptoms, for example, sometimes may be confused with drought injury; and, except that it usually occurs at a different time of the year, drought damage may be confused with *Peronospora* (downy mildew) injury. In other words, many causes and conditions may account for an abnormal appearance in grape vines, and growers should not jump too quickly to the conclusion that mineral deficiencies are to blame.

If a few affected or stunted vines occur nearly at random in a vineyard and they are surrounded by vigorous vines with normal green foliage, those affected should be inspected for fungal or virus diseases and for trunk injury by tillage implements, cold, or girdling. If the affected vines occur mainly in patterns that follow topography or a particular soil type that is not water logged, and if few if any normal superior vines are adjacent to those most affected, the symptoms are likely to be hunger signs.

The next step is to determine which element is deficient. Here the grower should study the accompanying color photos, and read the notes describing in detail the deficiency symptoms for each element. If, with these aids, he still is puzzled and in doubt, he should call in a specialist, such as a farm advisor, county agent, or processor's field service representative, for consultation. Generally, the experience of a specialist will be such that unless other factors are present to confuse the picture, he will be able to make a correct diagnosis, and if not, he usually will be prepared to collect leaf petiole samples by the proper procedure and have them evaluated by chemical analysis.

Finally, the proof of correct diagnosis usually is response to corrective measures. Depending upon the degree of confidence in the resulting diagnosis, the corrective fertilizer may be applied immediately over the entire affected vineyard, or over only a trial area for observation of response before further measures are given consideration.

NORMAL FOLIAGE

Cool weather in the first few weeks following bud break may cause all foliage on all vines to be light green and all shoots to grow slowly. These are not hunger signs in a diagnostic sense but the usual reaction of plants to weather too cool for normal growth (plate 13.)

NITROGEN (N) DEFICIENCY

Varieties such as Concord show a characteristic light green leaf color and reduced shoot growth from lack of nitrogen. A light pruning job in which too many growing points are left may intensify nitrogen deficiency symptoms. This factor should be taken into consideration in any diagnosis of shortage of this element. *Vinifera* varieties, such as Thompson Seedless, do not show recognizable visual symptoms of need for nitrogen until the deficiency is quite severe. If at harvest time in a mature vineyard, a trellis is less than three-quarters filled by leaves and no clear-cut symptoms of other deficiencies are apparent, the vines may be lacking in nitrogen. A more dependable method of determining nitrogen hunger in *vinifera* varieties is by means of the diphenylamine-sulfuric acid test. When properly applied, a blue color appears in sliced petioles when nitrate is present.

POTASSIUM (K) DEFICIENCY

If as little as 5 percent of the leaf area in a vineyard suffers leaf scorch, either as chlorosis or necrosis, a substantial loss of crop and of vine vigor will occur. Such symptoms often are confused with those of low magnesium. Two points should be kept in mind with regard to potassium deficiency: First, the lack of color begins at the extreme edges of the leaves rather than between the main veins, and the color change is first to a pale green or bronze, rather than to the more noticeable yellow or white of magnesium deficiency. Second, the mid-shoot leaves of the main canes rather than the basal leaves are the first to show the symptoms of pale color. On lateral shoots, the chlorosis is prominent on the apical leaves (plate 14). Vines severely deficient in potassium have compact clusters of small berries, the maturity of which is delayed or is uneven.

Another symptom related to low potassium is referred to as "black leaf." This symptom, shown in plates 15 and 16, is quite different from the edge chlorosis and leaf scorch heretofore discussed. The black color begins on the upper surfaces of exposed leaves and must be well advanced in order to show through to the lower surfaces. It has been reported in

vinifera vineyards in Germany, has been seen in the similar vineyards in California, but is more common in vineyards of the Northeast. The relation between black leaf and leaf scorch forms of potassium deficiency has not yet been clarified, but black leaf seems to be associated with overcropping of low-potash vines. Potash application reduces but does not eliminate it. The symptoms appear only on leaves most exposed to the sun.

MAGNESIUM (Mg) DEFICIENCY

The yellow or, with some varieties, reddish leaf discoloration associated with magnesium deficiency begins first between the main veins. To the casual observer, this chlorosis seems to begin at the leaf edges and move inward, but careful examination will show that the leaf edges stay green until a moderate-to-severe development causes all except the main veins at the leaf centers to become yellow. This clue together with symptom appearance developing first on the basal leaves are the best diagnostic signs of magnesium deficiency. At moderate degrees of

Courtesy of California Agricultural Experiment Station

Figure 2. Effect of zinc deficiency on Carignane grapes (right); poor set, and many shot berries. Left: Normal.

Courtesy of California Agricultural Experiment Station

Figure 3. Symptoms of boron deficiency at midsummer on Carignane grapes, in Mendocino County, California. Note that the chlorotic leaves are on the terminal portion of the shoot. Seeds are present in only the largest berries. In contrast to the behavior of Thompson Seedless, the small abnormal berries on Carignane do not shatter beyond this stage.

leaf chlorosis, magnesium deficiency does not reduce crop yields as much as leaf scorch of potassium deficiency (plates 17, 18).

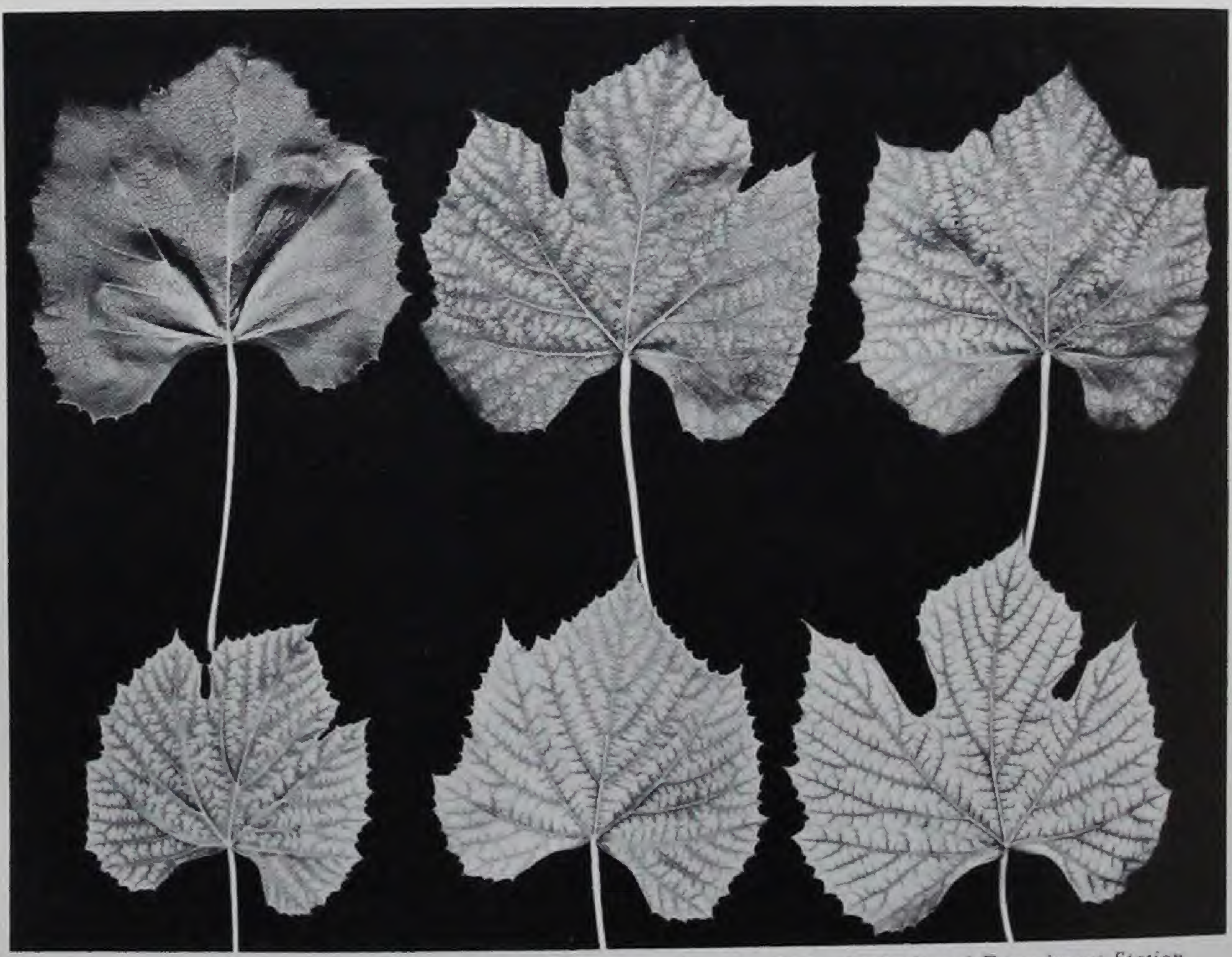
MANGANESE (Mn) AND ZINC (Zn) DEFICIENCIES

Manganese deficiency can seriously reduce vine vigor and crop yields. Signs of manganese shortage frequently are seen on the same Concord vines that show deficiencies of iron and/or potassium (figure 4). Mild symptoms can be found in most California vineyards, particularly those on poorly drained soils and those on soils that are high in pH. Symptoms seldom are so severe in California vineyards as to reduce crop yields, but knowledge of them is important so that they can be distinguished from those of zinc deficiency, (plates 21 and 22). The chlorotic leaf pattern is the same for both. The entire vein system is bordered by a distinct narrow band of normal green while the rest of the leaf is much lighter in color. Manganese deficiency signs develop on basal leaves which are not distorted or reduced in size unless the deficiency is very severe. On the other hand, with zinc deficiency, the symptoms show first on terminal leaves of main shoots and on leaves of lateral shoots that de-

velop in summer; these leaves are so much reduced in size that a synonym for zinc deficiency is "little leaf." The basal lobes of the leaf blades tend to draw away from the leaf stems or petioles as shown in plate 22 and figure 5. Zinc deficiency usually is accompanied by very poor fruit set that results in straggly clusters (figure 2). The symptoms usually are found in vineyards on sandy soils and certain rootstocks seem to be more susceptible than others.

IRON (Fe) DEFICIENCY

Iron deficiency also, is most severe on the youngest leaves of grape vines but differs from zinc deficiency in that the symptoms develop earlier in the growing season and have a different pattern. The loss of green color is more severe so that the leaf takes on a yellow or creamy white appearance with only the vein system remaining outlined by fine green lines; there is no green border effect, only the veins stay green. Iron deficiency seldom is a problem with *vinifera* varieties in California; it sometimes affects varieties in the Northeast, and is important in the Northwest (Plate 20).



Courtesy of James Beattie, Ohio Agricultural Experiment Station

Figure 4. Manganese deficiency at five stages on Concord grapes.

Courtesy of California Agricultural Experiment Station

Figure 5. Zinc deficiency on Tokay grape leaves. Note the apical position of the affected leaves and the lateral shoots with small leaves. Normal shoot tip at lower left.

BORON (B) DEFICIENCY

Boron deficiency is easily confused with several other disorders. Lack of boron (depending upon the variety) may result in a very light set of fruit with many flower clusters burning off entirely; or a set with a high percentage of shot berries; or an apparently normal set that shatters severely about midsummer. The symptoms to look for are the foregoing fruiting characteristics and a leaf chlorosis which is very similar to that caused by lack of magnesium. However, with low boron the first leaves to be affected are terminal rather than basal and the chlorosis moves

Courtesy of L. E. Scott, South Carolina Agricultural Experiment Station

Figure 6. Boron deficiency caused these terminal leaves to be misshapen on the Carmen variety of grapes at blossom time.

more rapidly to the leaf edges than in the case of low magnesium. The terminal shoot tips also may die back in early summer, a condition which results in growth of lateral shoots, often several from each node, that may be stunted but not otherwise show any symptoms of the deficiency. Observers must be careful in diagnosing boron deficiency in grapes that the chlorotic leaves are terminal on primary shoots rather than basal on secondary shoots (plate 19 and figures 3, 6).

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Courtesy of Frank D. Johanson

Plate 1 (upper left): Phosphorus deficiency symptoms on strawberry leaves. Plate 2 (upper right): Potassium deficiency on strawberry leaves. Plate 3 (lower left): Magnesium deficiency symptoms on strawberry leaves. Plate 4 (lower right): Boron deficiency symptoms on strawberry fruit.

Courtesy of W. E. Ballinger

Plate. 5. Upper surfaces of blueberry leaves showing nutrient deficiencies: phosphorus deficiency (upper left); nitrogen deficiency (upper right); potassium deficiency (lower left); calcium deficiency (lower middle right); healthy blueberry leaf (lower right).

Courtesy of W. E. Ballinger

Plate 6. Lower surfaces of blueberry leaves: phosphorus deficiency (upper left); nitrogen deficiency (upper right); potassium deficiency (lower left); calcium deficiency (lower middle left); magnesium deficiency (lower middle right); healthy blueberry leaf (lower right).

Courtesy of Ohio Agricultural Experiment Station

Plate 7. Light colored blueberry leaves are deficient in iron. Dark green leaves are healthy.

Courtesy of W. E. Ballinger

Plate 8. Early symptoms of magnesium deficiency on blueberry leaves.

Courtesy of W. E. Ballinger, North Carolina Agricultural Experiment Station

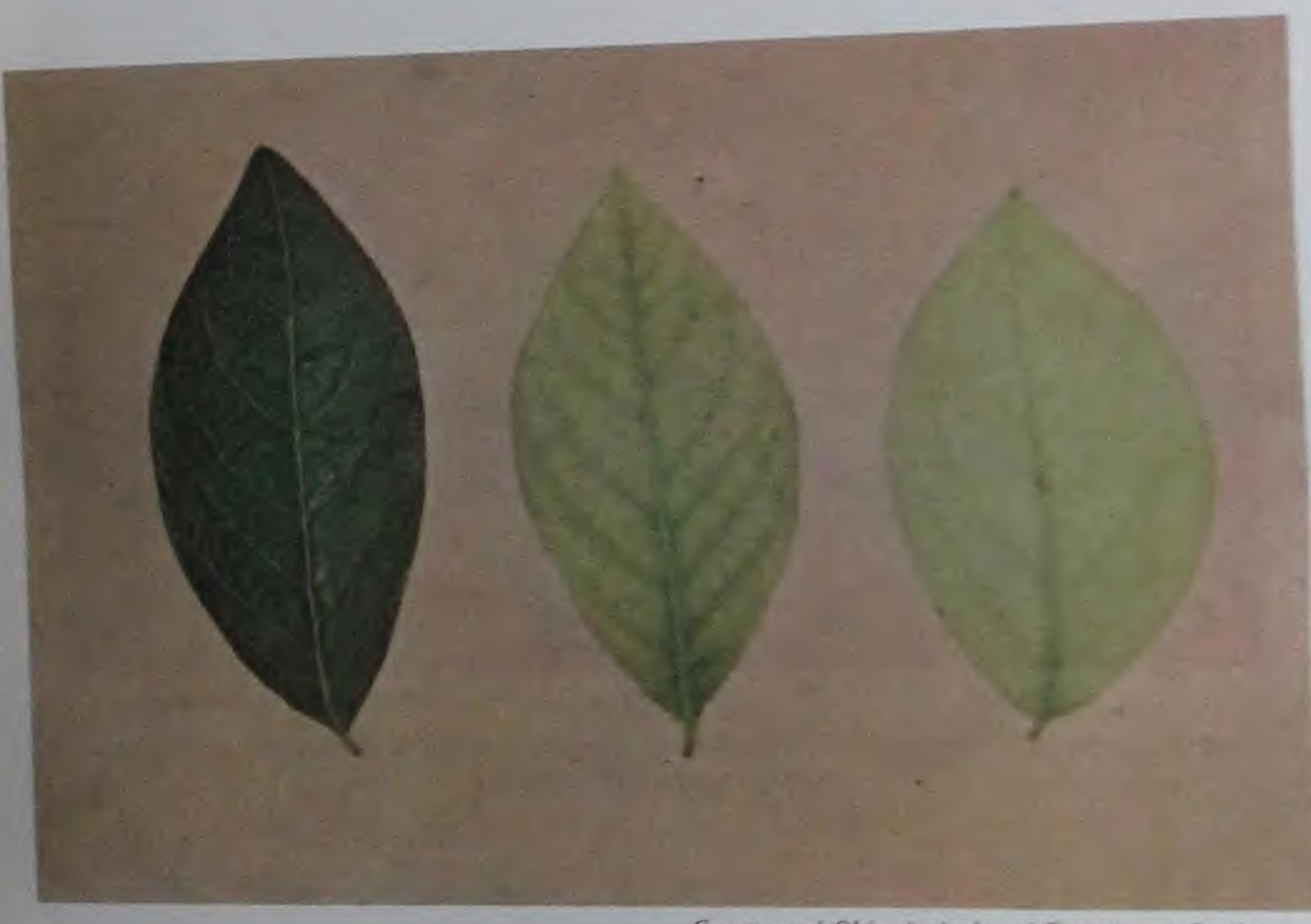
Plate 9. Nitrogen deficiency symptoms on blueberry leaves; healthy leaf (left).

Courtesy of W. E. Ballinger, North Carolina Agricultural Experiment Station

Plate 10. Phosphorus deficiency symptoms on blueberry leaves; healthy leaf (left).

Courtesy of J. S. Bailey, Massachusetts Agricultural Experiment Station

Plate 11. Magnesium deficiency symptoms on blueberry leaves; healthy leaf (left).

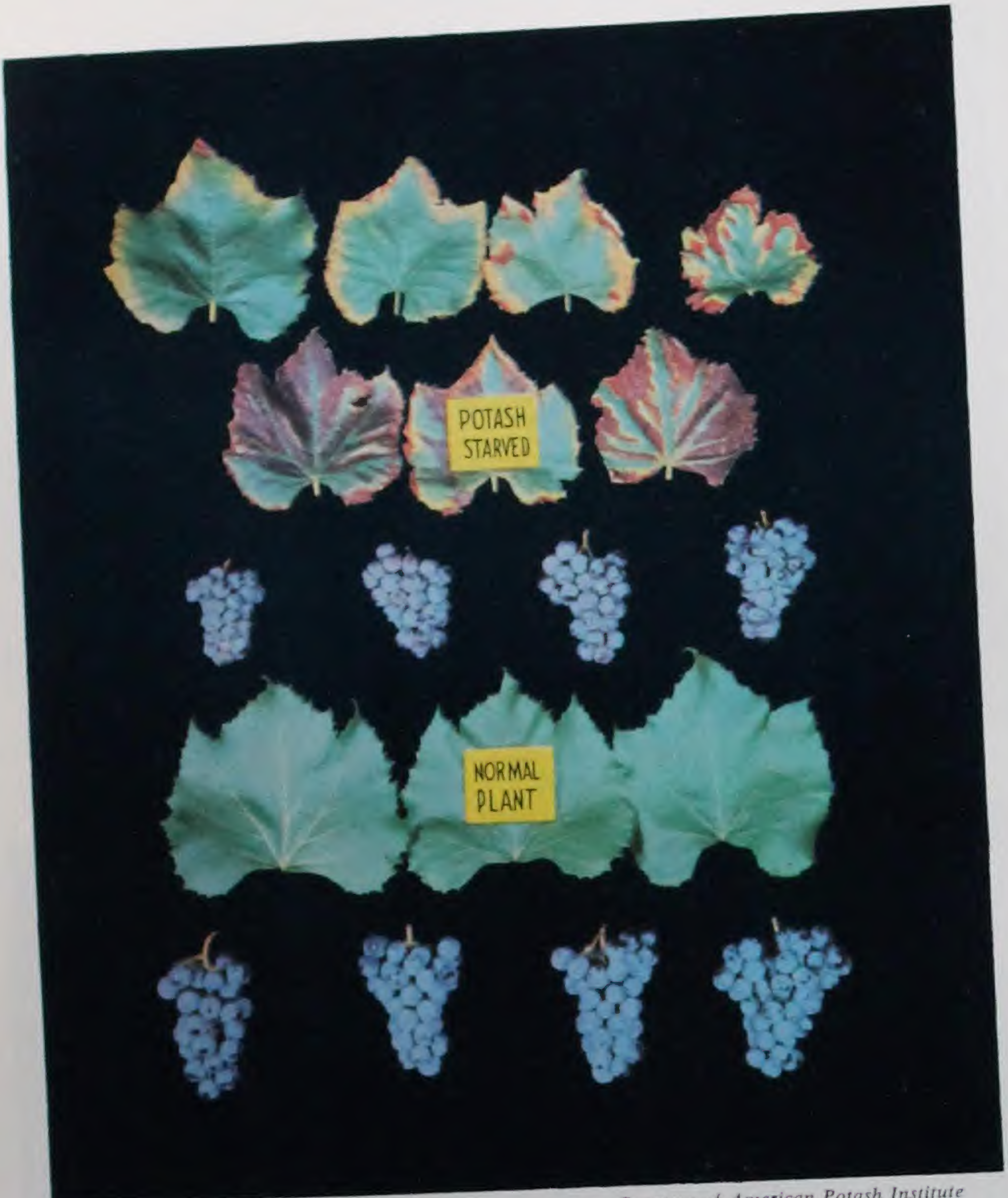


Courtesy of Ohio Agricultural Experiment Station

Plate 12. Iron deficiency symptoms on blueberry leaves; healthy leaf (left).

Courtesy of California Agricultural Experiment Station

Plate 13. Leaves of Carignane grape variety showing early-season potassium deficiency; normal leaf (right center).



Courtesy of American Potash Institute

Plate 14. Concord grape leaves showing several stages of leaf scorch due to potassium deficiency. The top four clusters are smaller due to this deficiency. Note that normal leaves are larger as well as free of chlorosis. Michigan, September, 1954.

Courtesy of James A. Cook

Plate 15. The black-leaf symptom found on heavily-cropped, low potash grapevines. The variety is Sauvignon vert, California.

Courtesy of W. J. Clore, Washington State University

Plate 16. The black-leaf symptom on Concord grapes. It is inter-veinal on leaves well exposed to the sun. Washington, October, 1957.

Courtesy of North Carolina Grape Agricultural Experiment Station

Plate 17. Four stages of magnesium deficiency on leaves of *V. rotundifolia*, October, 1961. Normal leaf, lower right.

Courtesy of New York Agricultural Experiment Station

Plate 18. Magnesium deficiency of Concord grapes. New York, October, 1953.

Plate 19. Shoot tip of Thompson Seedless grapes in mid-July, showing symptoms of boron deficiency. Note death of the main growing point and the short internodes near the tip. The chlorosis of the leaves on the main shoot becomes worse near the tip while the regrowth on the lateral shoot shows normal appearing leaves.

Courtesy of California Agricultural Experiment Station

Plate 20. Iron deficiency on Concord grapevine characterized by creamy white leaves, excepting veins, on apical portion of shoot. New York, August, 1952.

Courtesy of New York Agricultural Experiment Station

Courtesy of James Beattie

Plate 21. Manganese deficiency on Concord grapes. Ohio, August, 1955.

Courtesy of California Agricultural Experiment Station

Plate 22. Zinc deficiency symptoms showing chlorosis of grape leaves on a terminal shoot and wide angles of leaf petioles and leaf blades. This is a shoot tip of Tokay in mid-summer. California.

CHAPTER XI

Nutrient Deficiencies in Citrus

By Winston W. Jones and Paul F. Smith *

DEFICIENCIES of one or more mineral elements are widely distributed throughout the citrus growing areas of the world. However, extensive research has led to the development of control measures that have strongly reduced nutrient deficiencies as limiting factors in citrus growing. This does not mean that all the problems of citrus mineral nutrition have been solved or that growers no longer are concerned with deficiencies. Constant vigilance is required to maintain an optimum mineral nutritional level for maximum production of high quality fruit. Both leaf and fruit symptoms and leaf analysis for mineral elements now are used as guides in formulating fertilizer recommendations. Leaf symptoms of excesses are as apt to be encountered as those of deficiencies. In cases where symptoms are not distinguishable, leaf analyses frequently are helpful. In the following discussion particular attention is given to deficiencies which commonly occur in the field. Both leaf symptoms and leaf content of elements are considered. A key at the end of this chapter summarizes deficiency symptoms in citrus leaves.

LEAF ANALYSIS

Leaf symptoms for any single element deficiency are similar for most cultivated citrus species and varieties. Thus, zinc deficiency symptoms are approximately the same, be they on orange, grapefruit, lemon, or other citrus trees. However, leaf analysis standards are based largely on oranges and may require some modification for other species.

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* Winston W. Jones is Professor of Horticulture and Horticulturist, Agricultural Experiment Station, University of California, Riverside, California; Paul F. Smith is principal plant physiologist, Agricultural Research Service, Crops Research Division, U. S. Department of Agriculture, Orlando, Florida.

They express deep gratitude to the authors of previous editions for illustrations and background information. Portions of the previous text have been incorporated with new information in an attempt to more fully depict the various deficiencies. The present authors hope that the addition of new information and new interpretations will enhance the usefulness of an invaluable previous chapter. Original authors were A. F. Camp, Vice Director, Florida Agricultural Experiment Station, University of Florida; H. D. Chapman, Chairman of Division of Soils and Plant Nutrition, University of California Citrus Experiment Station; and E. R. Parker, Chairman, Division of Orchard Management, University of California Citrus Experiment Station.

Leaf analysis is starting to be widely used in various parts of the world as a diagnostic tool to evaluate the nutritional status of citrus. Research so far shows fairly consistent leaf values associated with deficiencies, satisfactory levels, or excesses, even though the trees may be growing under widely different soil or climatic conditions. This, of course, requires use of similar methods of sampling and adequate analytical procedures. Prudent orchard management and fertilizer practice requires a knowledge of the nutritional status of the trees.

As a general guide, leaf analysis values are grouped into three rather broad categories in the list which follows. These values are based on work done in the two major citrus growing areas of the United States—Florida and California. Intensive study in any given area may lead to some refinement or narrowing of ranges for a particular set of conditions. The purpose of this listing is to provide a simple guide by which a nontechnical person can make some evaluation if he can obtain analytical data.

These tentative general ranges are for the guidance of growers in interpreting citrus leaf analyses. Based on concentrations found in 4- to 7-month-old bloom cycle leaves from non-fruiting terminals, they are adapted from the work of Reuther, Embleton, and Jones (66):

Essential element	Deficient	Satisfactory	Excess
		per cent	
Nitrogen—N	<2.3	2.4 –2.8	>2.9
Phosphorus—P	<0.09	0.10–0.17	>0.18
Potassium—K	<0.7	0.8 –1.6	>1.7
Calcium—Ca	<2.5	2.6 –5.5	>5.6
Magnesium—Mg	<0.20	0.21–0.50	>0.51
Sulfur—S	<0.19	0.2 –0.5	>0.6
		parts per million	
Boron—B	< 25	26 –250	>260
Copper—Cu	< 4	5 – 16	> 17
Zinc—Zn	< 19	20 – 50	> 51
Manganese—Mn	< 19	20 – 90	>100
Iron—Fe	< 35	36 –120	>130
Molybdenum—Mo	<0.06	0.07–0.25	>0.3

< = less than
> = more than
Excess = No chance that higher amounts will be beneficial; toxicity symptoms occur only with much greater amounts.

For a trained observer, leaf analyses are not an absolute requirement in diagnosing critical deficiencies such as depicted in this chapter. In fact, deficiency symptoms were described well before leaf values were known. Development of severe visible deficiency symptoms, however, requires many months or years of stress. One of the primary virtues

of leaf analyses is that they enable detection of impending deficiencies so that they may be corrected before serious losses in production or a lowering of fruit quality occurs.

The values in the list are somewhat arbitrary. Some orchards, for instance, may show 0.7 percent K and probably will not benefit by an increase in leaf potassium (K). As a rule, however, fruit size will be smaller than desirable at this level if no other factors limit growth. The column headed "deficient" actually means that a visible symptom, a lowering of production, or some effect on fruit quality may be expected at about the level shown. The certainty of such a reaction increases as the nutrient level drops below the indicated value. By the same token, the values shown as "excess" do not mean a toxic condition, but a state where virtually no chance exists that a higher level will be beneficial. If a toxic condition exists, however, values greater than those shown are likely to be found.

The ranges shown as "satisfactory" are rather narrow for some elements and quite broad for others. As a rule, however, any set of values that falls within the bounds shown will be from a healthy tree, the performance of which probably is not being handicapped by faulty nutrition. The ideal condition is near the center of the range shown for each value. A tree having a leaf analysis that falls in the center of the satisfactory ranges is not likely to be distinguished from others having values that fluctuate between the various extremes of the ranges. Periodic sampling shows trends of nutrition. A consistent pattern of about 0.8 percent K year after year, for instance, arouses no concern about potash. If the K level gradually decreases from 1.4 percent down to 0.8, however, the decline indicates that the K supply is diminishing or the fertilization level of potash is inadequate. Leaf analysis thus provides early warning of impending deficiencies or excesses.

Unfortunately tissue analysis is not an easy or simple process. Aside from the difficulties of careful sampling and obtaining reliable analytical data, many factors affect interpretation of results. The supply of one element is influenced by that of others so that the matter of balance comes into play. A shift in the supply of nitrogen can affect the levels of nearly all of the other elements found in the leaves. Other elements likewise influence one another. For this reason interpretation of leaf analyses must remain somewhat flexible.

For more detailed discussion on the interpretation of tissue analyses and the use of leaf standards for guidance, recent reviews should be consulted (66, 71).

NITROGEN (N) DEFICIENCY

SYMPTOMS

Deficiency symptoms that respond to applications of nitrogen are almost too well known to need description, but since they may be confused with other symptoms in some instances, attention is called to some of their outstanding characteristics.

Since nitrogen is a part of chlorophyll, the green pigment in leaves, a shortage of nitrogen results in reduction in the amount of chlorophyll and loss of green color. Typically, the first symptoms of nitrogen de-

Courtesy of California Agricultural Experiment Station

Figure 1. Nitrogen deficient Washington navel orange tree (left) and comparable tree (right) which was supplied with nitrogen in the form of urea. Winter cover crops were grown in each case. In contrast with the fertilized tree, the deficient tree had sparse foliage of a light green color, while some leaves were distinctly yellow. New growth was very limited, and crop production had dropped to a very low level.

ficiency appear as a uniform light green to yellowish-green color of the leaves. If nitrogen is deficient when growth begins, the young leaves are undersized, thin, fragile, and pale in color. Shedding of old leaves is heavy on such trees and consequently, their foliage is sparse. This type of symptom is common in unfertilized trees (plate 1 and figure 1). Considerable twig dieback occurs and the trees look brushy. Such trees seldom die but remain in a permanently stunted condition unless nitrogen is supplied in adequate amounts.

The degree and the time that a deficiency appears are important. Trees under severe, continuous deficiency do not produce commercial

crops of fruit. Adequate amounts of nitrogen are required for flowering and fruit setting. After fruit set, however, a mild, temporary nitrogen deficiency, as based on leaf symptoms, may result in improved fruit quality (38).

A leaf symptom sometimes associated with nitrogen deficiency is shown in plate 3. Here, the tissue along the midrib and the larger veins is distinctly lighter in color than the remainder of the leaf. This symptom is not specific for nitrogen deficiency since it develops following girdling of twigs, limbs, or trees, or following root injury from fungi or from fluctuating water tables. Such leaves are likely to have an abnormal chemical composition and to show deficiencies of a number of elements; applications of specific nutrients for correction are not beneficial.

HISTORY AND REMEDY

The earliest references on citrus culture refer to use of manures or other nitrogenous materials. Most soils do not contain a continuing supply of nitrogen; hence, it must be added to avoid a deficiency. The fact that nitrogen is lost on ashing of plant material for chemical analyses slowed the development of information on the need of plants for this element. Research did not definitely show until about 1850 that plants will respond to soil applications of inorganic nitrates. About 1918, the relation of nitrogen to fruitfulness in plants was demonstrated.

Since nitrogen deficiency usually is caused by a lack of nitrogen in the soil, the obvious remedy is to supply this element in required amounts. The problem then is one of determining the right amounts and the time of application. Tissue analysis combined with observation of grove conditions and history of previous grove practices appears to be the best method of determining the amount of nitrogen to apply. If nitrogen is required, it should be applied several weeks previous to flowering. Where regreening of fruit is a problem, late spring or summer applications of nitrogen accentuate this characteristic (38, 42).

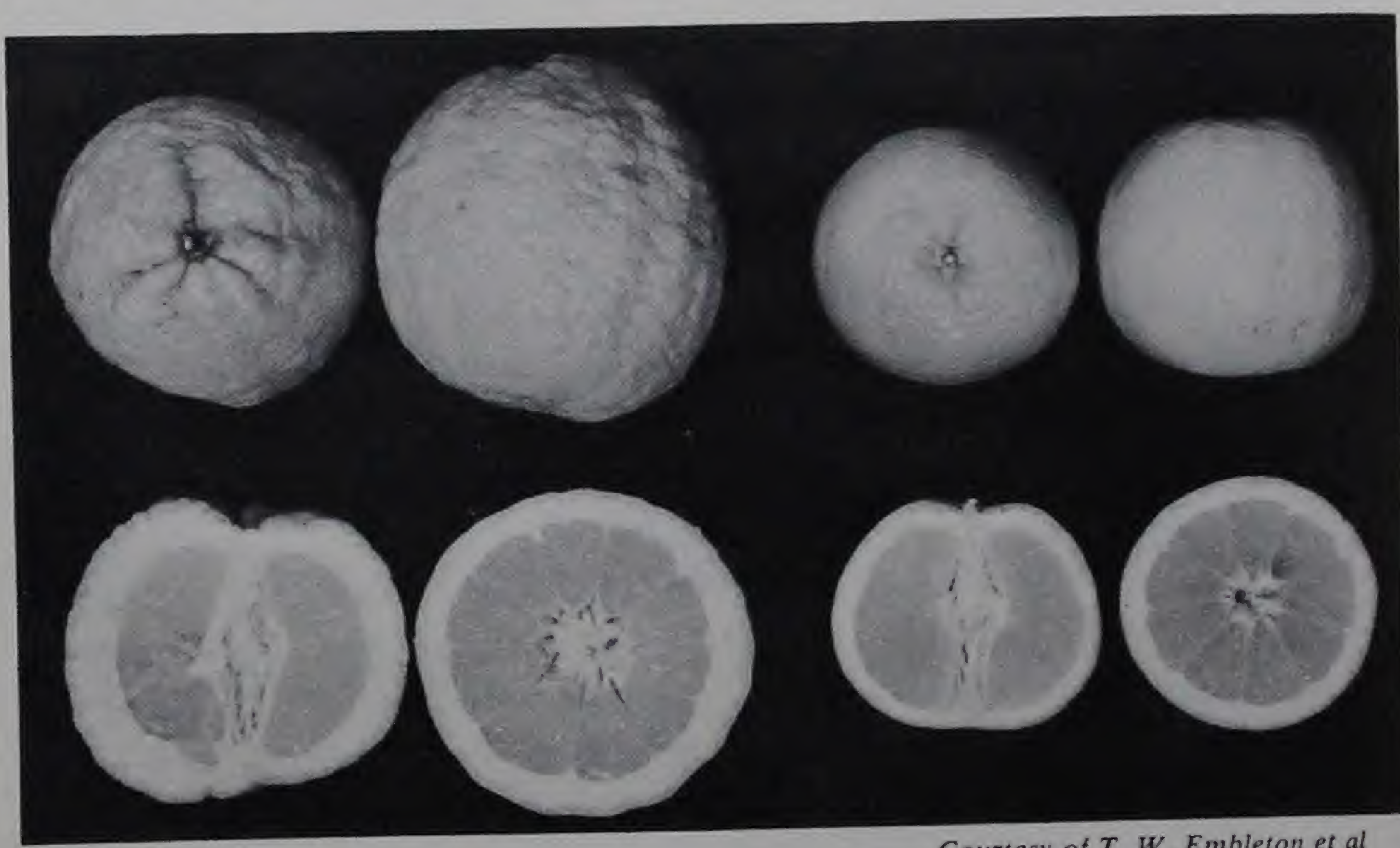
Depending on the conditions under which nitrogen is used, the source of this element may be important. Nitrogen from nitrates is more quickly available than from other sources but is more subject to leaching. Some ammoniacal nitrogen may be lost by volatilization under certain conditions (23, 47, 86). Continued use of nitrate of soda and ammonium sulfate may produce harmful effects on the soil and interfere with water penetration (40). In light soils, ammonium sulfate tends to cause excessive subsoil acidity and increases lime re-

quirements more than other nitrogen supplying materials. Other sources may contain excessive amounts of perchlorate (81) or of biuret (37, 41, 62). Urea foliage sprays have been used to some extent in California where properly timed nitrogen applications of this kind have been beneficial. No special benefit has been obtained from nitrogen sprays in Florida.

PHOSPHORUS (P) DEFICIENCY

SYMPTOMS

Early work on the development of phosphorus deficiency symptoms was done in soil, sand, and solution cultures (12, 14). Symptoms developed under field conditions have been described both in Florida (27) and in California (19). In the development of symptoms, effects



Courtesy of T. W. Embleton et al

Figure 2. Valencia oranges from trees deficient in phosphorus (left) and fruit from phosphorus-treated trees (right). Note differences in size, shape, coarseness, thickness of peel, and hollow centers.

on fruit quality are first noticeable. Fruits becomes large, coarse, and misshapen, with exceptionally thick peels and hollow centers (figure 2). Fruits from deficient trees are exceptionally high in acid (21) and a reduction in acid may be the only measureable response to phosphorus applications (39, 76) where a deficiency is borderline.

Following deterioration in fruit quality, foliage density becomes progressively thinner. The leaves produced are few and small and drop

Courtesy of T. W. Embleton et al

Figure 3. Phosphorus deficiency in oranges. Note the thin foliage, small leaves, lack of fruit, and leaves on the ground of deficient tree (left). Response two years after treatment is illustrated by the tree on the right.

prematurely (figure 3). Accompanying the reduction in foliage density is a loss in yield. Deficient trees produce only a weak spring flush of growth and by fall their leaves have a bronzed cast. Some twig dieback occurs. There are no specific leaf symptoms for phosphorus deficiency, although some necrotic (dead) areas have been reported as being associated with this deficiency (14), especially with lemons (1).

HISTORY AND REMEDY

The cause of phosphorus deficiency either is lack of phosphorus in the soil, or lack of available phosphorus. Citrus appears to be able to obtain phosphorus from the soil more readily than many other plants. Citrus grows freely in Florida and Brazil on soils which are so low in phosphorus that corn, cotton, and many other crops will not grow properly without phosphate fertilization. Phosphorus deficiency in citrus in the field is not common. In a study of water-soluble, acid-soluble, and total phosphorus contents of soils in a series of healthy and phosphorus-deficient citrus orchards, Aldrich and Buchanan (2) found no correlation between water-soluble and acid-soluble phosphorus and incidence of phosphorus deficiency symptoms. But they did find that deficiency was correlated with a low total phosphorus supply.

Use of phosphatic fertilizers provides corrective treatment though difficulty sometimes is experienced with soils of high phosphorus-fixing power and where the rooting systems of trees are deep. Phosphorus does not move readily in the soil. Once enough has been added to correct a deficiency, additional quantities should not be applied as excesses tend to interfere with absorption of iron and zinc. A deficiency is more rapidly corrected by one or more heavy doses than repeated light, annual applications of phosphatic materials. Leaf analysis is a good indicator as to whether or not phosphorus should be applied.

Phosphorus foliage sprays have been tried with only limited success.

POTASSIUM (K) DEFICIENCY

SYMPTOMS

Critical potassium deficiency in citrus probably was first encountered in Australia, where a severe decline and burned-leaf condition was corrected (6) after several years of potash application. Chlorosis, gumming of twigs, small, curled and puckered leaves, premature fruit shedding, and other symptoms have been associated with potassium deficiency. Smith and Rasmussen (73) describe the development of

symptoms as follows: In late summer, a blotch-type chlorosis started to develop in many 5- to 6-month-old leaves. At first this appeared to be merely a loss of chlorophyll in large spots without clearly defined borders. Such areas were nearly always in the apex halves of the leaves but sometimes along their sides, while basal and terminal portions of the blades were normal green. Subsequently, these areas tended to spread, coalesce, and turn yellow (figure 4). By January the color of many leaves had deepened from pale yellow to golden bronze resem-

Figure 4. Potassium deficiency in grapefruit leaves. Typical chlorosis patterns in 1-year-old leaves.

Courtesy of Smith and Rasmussen

bling the bronze associated with magnesium deficiency. There was, however, little or no shedding of affected leaves. Prolonged severe deficiency causes leaf tip necrosis or "burn."

Fruit symptoms of potassium deficiency include a reduction in size of fruit and a very thin peel of smooth texture (figure 5, plate 2). A decrease in total acidity of the fruit also occurs and a consequent increase in the solids/acid ratio.

HISTORY AND REMEDY

The literature on the effects of potassium deficiency in citrus groves is somewhat contradictory. This was brought about, to a large extent, by two factors: first in many early experiments the only problem that was studied was the effect of potassium applications on a particular

soil, without knowledge as to whether the trees involved were actually deficient or not, and second, in many later experiments the existence of other deficiencies interfered with interpretations of results. In the latter case, situations are complicated by the interaction of potassium, magnesium, and calcium in plants. In some of the early work in Florida, increased magnesium deficiency was brought on by excessive potassium applications. Early potash sources often contained considerable magnesium and their use so greatly improved tree condition that more and more potash was used. When potash salts of greater purity came into use, severe magnesium deficiency was induced. Also, in California applications of potassium through the continuous use of manure has intensified the incidence of magnesium deficiency. A considerable body of knowledge now has accumulated from controlled culture and from field studies, and leaf levels for potassium are well established.

Courtesy of California Agricultural Experiment Station

Figure 5. Fruit from potassium deficient tree (left) compared with fruit from trees of similar age receiving ample potassium. Note reduced size and smooth rind of fruit lacking potassium; also reduced leaf size and malformation.

To correct potassium deficiency, adequate amounts of potassium should be applied in the fertilizer. It can be supplied from potassium chloride, potassium sulfate, or by animal manures. In light sandy soils,

from which potassium is readily leached, small annual applications appear to be desirable (63). In heavy soils one or two large applications are needed to give a response and this will then last for several years. Leaf analysis works very well to determine the potassium status of a citrus tree.

CALCIUM (Ca) DEFICIENCY

SYMPTOMS

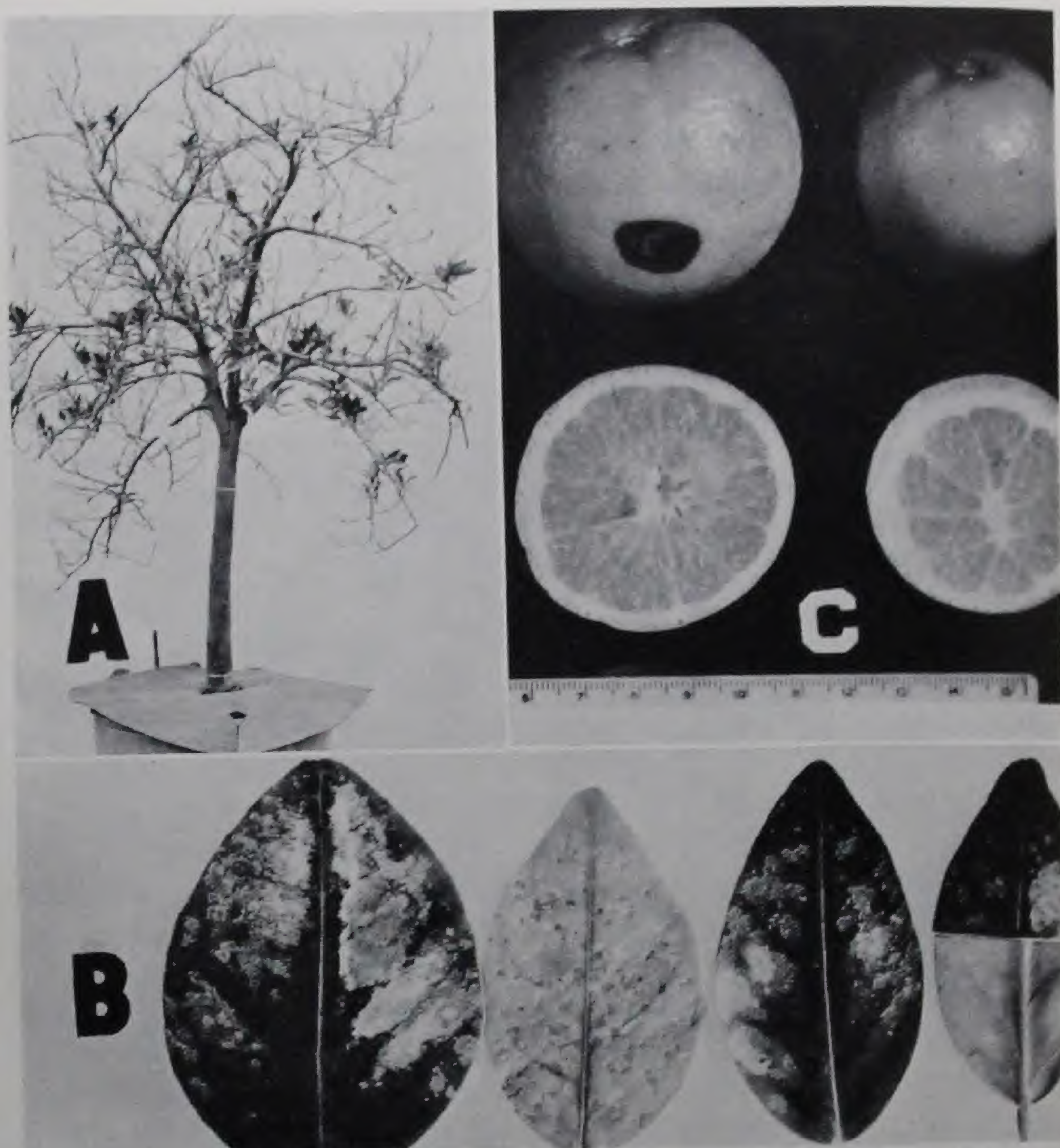
Calcium deficiency symptoms on citrus are very rare. Symptoms produced in sand cultures, illustrated in figure 6 and plate 4, appear to be related to high potassium or to low or high magnesium contents. In soil cultures in which calcium occupied only 8 percent of the exchange complex of the soil colloids, and leaf calcium was only 0.47 percent, Martin and Page (48) obtained some reduction in growth of citrus seedlings and stated that "a presumed calcium deficiency caused leaf necrosis and may have contributed toward the death of some of the plants." In many plants, death of the terminal buds is the first symptom of calcium deficiency (43). (See also Chapter IV on tobacco.)

Recently Spencer and Koo (78) reported calcium deficiency symptoms on field-grown trees. These appear to be true symptoms of calcium deficiency since they are not complicated with known excesses or deficiencies of other elements. Spencer and Koo describe the symptoms as a chlorosis along the leaf margins and between the main veins (figure 7). Many of the leaves on calcium deficient trees were smaller and somewhat thickened. In some instances the leaves had short midribs resulting in a heart-shaped appearance. Premature drop of foliage and dieback of twigs, followed by weak growth of lateral buds resulted in a rosetted multiple bud effect on many smaller branches. The chlorotic leaves contained approximately 0.24 percent calcium as compared with 2.4 percent in green leaves from healthy trees.

Misshapen fruits were more prevalent in calcium-deficient trees.

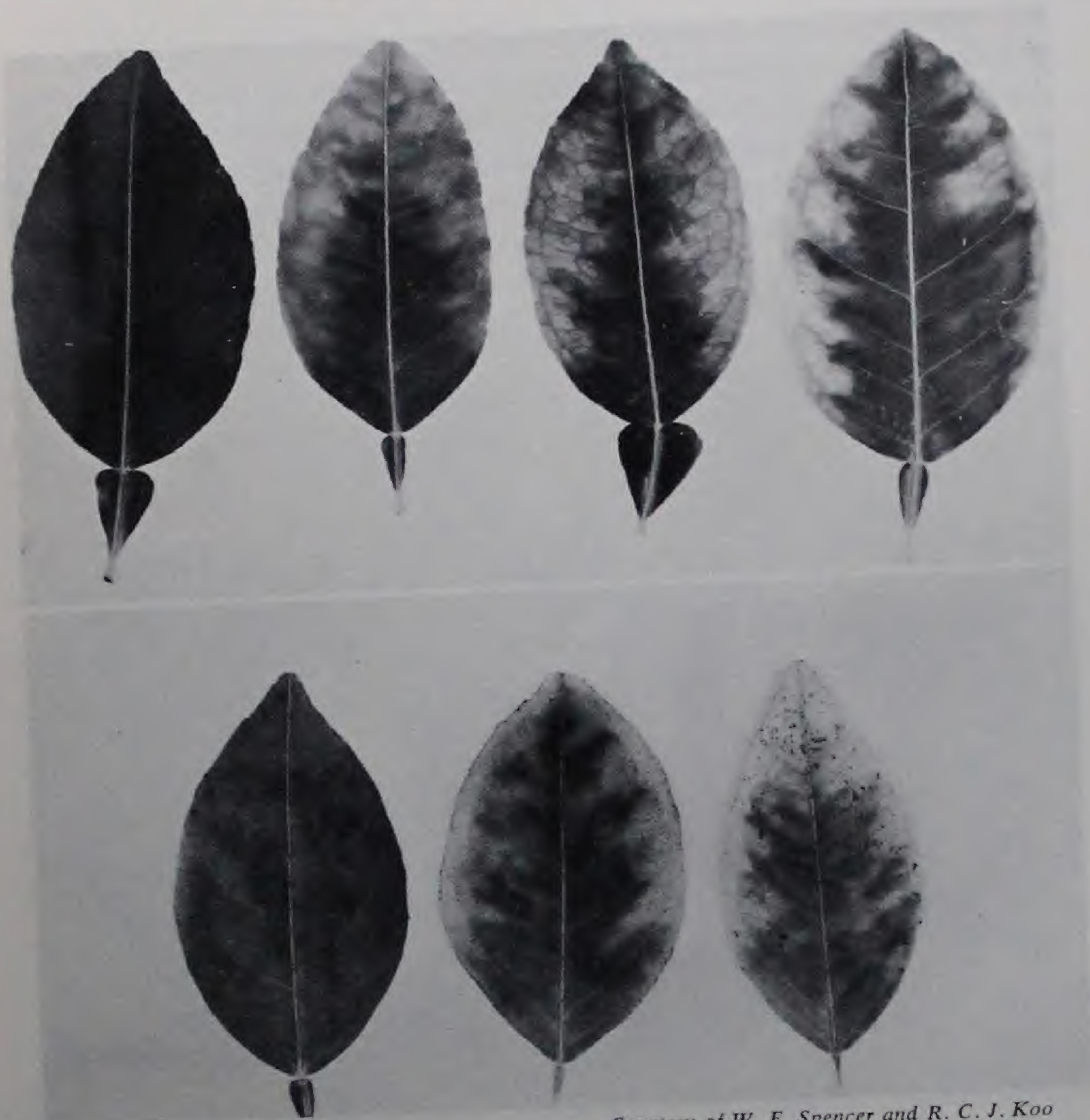
HISTORY AND REMEDY

That calcium deficiency will ever be a commercial problem in the field appears rather doubtful. In the very acid sands of Florida, native calcium may be sufficiently low to cause a deficiency but in practice calcium as ground limestone is added in the pH control program. This is more than enough calcium to supply all nutritional requirements.



Courtesy of California Agricultural Experiment Station

Figure 6. Calcium deficiency symptoms on Valencia oranges growing out of doors in sand cultures: A, showing extreme defoliation and dieback of trees supplied with high potassium; with high magnesium and low potassium defoliation was not nearly so severe. B, leaf necrosis of upper side of leaf under conditions of potassium excess; the under side of the leaf was not affected; leaves from trees supplied with high magnesium and low potassium showed no such burn. C, fruit from calcium-deficient trees showing small size, and partially gelatinized and shrivelled juice vesicles. The tree from which this fruit came was supplied with a low level of potassium and a high level of magnesium. Fruit from calcium-deficient, high-potassium trees was large with a very coarse rind texture, in contrast to that shown here.



Courtesy of W. F. Spencer and R. C. J. Koo

Figure 7. Calcium deficiency symptoms in leaves. Ruby Red grapefruit (above); Pineapple orange (below). Control leaf on left in each case contained about 2.4 percent Ca; chlorotic leaves about 0.24. Specks on orange leaves are from melanose fungal infection and is not related to the deficiency pattern.

Spencer and Koo (78) were able to prevent calcium deficiency by application of limestone or triple superphosphate. Both of these materials, of course, contain calcium. No other work under field conditions has been reported.

MAGNESIUM (Mg) DEFICIENCY

SYMPTOMS

Symptoms of magnesium deficiency may occur on citrus leaves at any season of the year but commonly develop in the late summer or

fall when the fruit crop is maturing (9). The leaves on which the symptoms appear usually are mature and normal in color up to that time. Irregular yellow blotches start along the midribs and eventually coalesce to form irregular yellow bands on each side (plate 5). Such areas enlarge until only the tips and bases of the leaves are green, the bases showing more or less inverted V-shaped areas pointed on the midribs. This fading from green to yellow does not follow a fixed pattern. In acute deficiencies, the leaves eventually become entirely

Figure 8. Grapefruit trees acutely deficient in magnesium showing extreme defoliation in the fall of the year, with fruit left unprotected because of lack of foliage.

Courtesy of Florida Agricultural Experiment Station

yellow and are shed (figure 8); however, if the deficiency is only moderate the patterned leaves may remain on the trees for a long time.

Varieties producing seedy fruit are more severely affected than varieties producing seedless fruit. Heavily fruited limbs may develop extreme deficiency symptoms and may even become completely defoliated, while adjoining limbs with little or no fruit show no symptoms. Severe deficiency results in a great reduction in total crop and according to Sites (68) the fruits are low in soluble solids, total acid, and Vitamin C. A lessening of pigmentation of fruit occurs to pale orange or light yellow. Deficient trees are more susceptible than healthy ones to cold injury (45) (figure 9).

HISTORY AND REMEDY

Averna-Sacca corrected a chlorotic condition in citrus in Brazil with magnesium compounds in 1912 (3). In 1924, Reed and Haas induced magnesium deficiency in sand cultures and described the foliage symptoms (61). "Bronzing," as it is called in Florida, has been known since the last century but its correction by the use of magnesium was not

Courtesy of Florida Agricultural Experiment Station

Figure 9. Effects of freeze in Florida on trees which were supplied with nitrogen, phosphorus, and potash, but were deficient in magnesium, manganese, copper, and zinc (foreground). Undamaged trees supplied with the latter elements (background).

achieved until 1936 (7, 83). Until recently this deficiency has not been a serious problem in California (22) but at present mild leaf deficiency symptoms are widespread. Magnesium deficiency has been reported from most of the citrus growing areas of the world.

In California soils, potassium generally decreases and magnesium increases with depth (59). Over a 28-year period in a long-term fertilizer experiment on Washington navel orange trees at Riverside, California, decreases in exchangeable magnesium in the soil were highly correlated with amounts of salts added as fertilizers or soil amendments (57, 58). Addition of chemical fertilizers or manures to many crops

increased the magnesium losses from the soil (35). Apparently, magnesium is being moved downward in the soil and deficiency of this element is likely to be more of a problem in the future. The amount of magnesium available to orange trees from the soil depends in a large measure on the potassium/magnesium ratio in the soil within the root zone (49, 59); similar observations were made in studies with apple trees (18). Reports too numerous to list here show that magnesium deficiency of plants frequently is induced or aggravated by applications of materials containing potassium. The magnesium level in leaves generally is positively correlated with their nitrogen content (64). This relationship is such that in cases of borderline magnesium deficiency low nitrogen increases requirements while applications of nitrogenous fertilizers eliminate them.

In acid, sandy soils of Florida, much magnesium is supplied by applications of dolomite, magnesium carrying limestone, used for pH control. This is supplemented with water soluble magnesium salts, usually sulfate, in fertilizers (63). Except for the sandy soils in Florida, soil applications of magnesium have not been effective in correcting this deficiency (20, 34, 49, 52). Neither have magnesium sulfate foliage sprays been effective (34).

However, Embleton and Jones (22) report successful control of magnesium deficiency by foliage sprays of magnesium nitrate. Its use at the rate of 10 pounds per 100 gallons of water, applied when the spring flush of growth was about two-thirds expanded, resulted in an increase in the magnesium content of the leaves and the elimination of deficiency symptoms. If the deficiency is severe, more than one application per year may be required.

SULFUR (S) DEFICIENCY

SYMPTOMS

Sulfur deficiency has not been identified in the field. The following description is of results from sand and soil cultures of Chapman and Brown (11). The leaf symptoms in general consisted of a chlorosis quite similar to that produced by nitrogen deficiency. Sulfur deficiency, however, was characterized at its onset by much yellower new growth, the older leaves remaining green (plate 6). This contrast in coloration was marked and gave the trees a striking appearance. No abnormal twig characteristics developed, but some dying back occurred as the deficiency progressed (figure 10). Immature fruits from sulfur-deficient

Figure 10. Effects of acute sulfur deficiency on oranges, showing weak multiple and highly chlorotic shoots (foreground).

Courtesy of California Agricultural Experiment Station

trees were a lighter green than normal and mature fruits were a lighter orange. Some fruits were dwarfed and misshapen and others had abnormally thick peels. Interiors of fruits were pulpy and juiceless, with some of the juice sacs gelatinized.

ZINC (Zn) DEFICIENCY

SYMPTOMS

Zinc deficiency also is referred to as "frenched-leaf," "frenching," or "mottle-leaf." Like most of the metal deficiencies, it develops only on new growth. Leaf size is reduced somewhat in proportion to the scarcity of zinc. When only a slight deficiency exists, leaf size and twig length are only slightly reduced. When the deficiency is severe, leaf

size is drastically reduced and twig length greatly shortened. Probably because of the compression of growth and reduction in leaf size, the new growth has a bushy, upright appearance.

By far, the most distinctive aspect of zinc deficiency is the pattern of chlorosis. The creamish-yellow mottle on the dark-green background of the remainder of the leaf, in all its variations, presents a striking and easily identifiable pattern (plate 7) but seriously hampers tree performance unless corrected in its early stages. When the deficiency is mild only a few terminals may show symptoms and these may gradually disappear with time. Each succeeding flush of growth, however, is apt to show an increasing incidence of symptoms until nearly all terminals are affected and the condition becomes persistent. Typically, lower shoots on the south or southwest sides of trees are the first to show symptoms, but with continued stress whole trees become affected. In some cases, trees become unthrifty and show small, upright leaf growth with little or no chlorosis, but such behavior is exceptional.

When zinc deficiency is very mild, it may not appreciably alter normal

Figure 11. Zinc deficiency pattern on orange leaves.

Courtesy of California Agricultural Experiment Station

Courtesy of California Agricultural Experiment Station

Figure 12. Acute symptoms of zinc deficiency in orange twigs showing small leaves, chlorosis and dying back.

tree growth. A transient mottling of a few young leaves may be the only symptom. With a somewhat greater degree of deficiency the young growth starts out in normal fashion but pronounced mottling or yellowing of lateral areas of the blades develops as the leaves expand. The terminal leaf or leaves may be slender and reduced in size and show strong mottling but the leaves are persistent (figure 11). In cases of severe deficiency, new leaves may emerge as tiny, slender, whitish structures with little or no green color. They do not enlarge greatly and with time their midrib and lateral veinal areas may become green (figure 12). Such leaves tend to shed early and the short twigs may die back. After a prolonged time the larger twigs in turn die back so that the tree appears brushy (figure 13). Trees may sucker out from the trunk or main branches with nearly normal growth for a time, but the suckers in turn develop deficiency symptoms as more growth continues.

Mild zinc deficiency has little or no effect on fruiting or fruit quality. As the severity approaches an acute stage, however, fruits decline in number and their pulp becomes dry, woody, and insipid. Fruits in extreme cases are small, misshapen, and lose their green color pre-

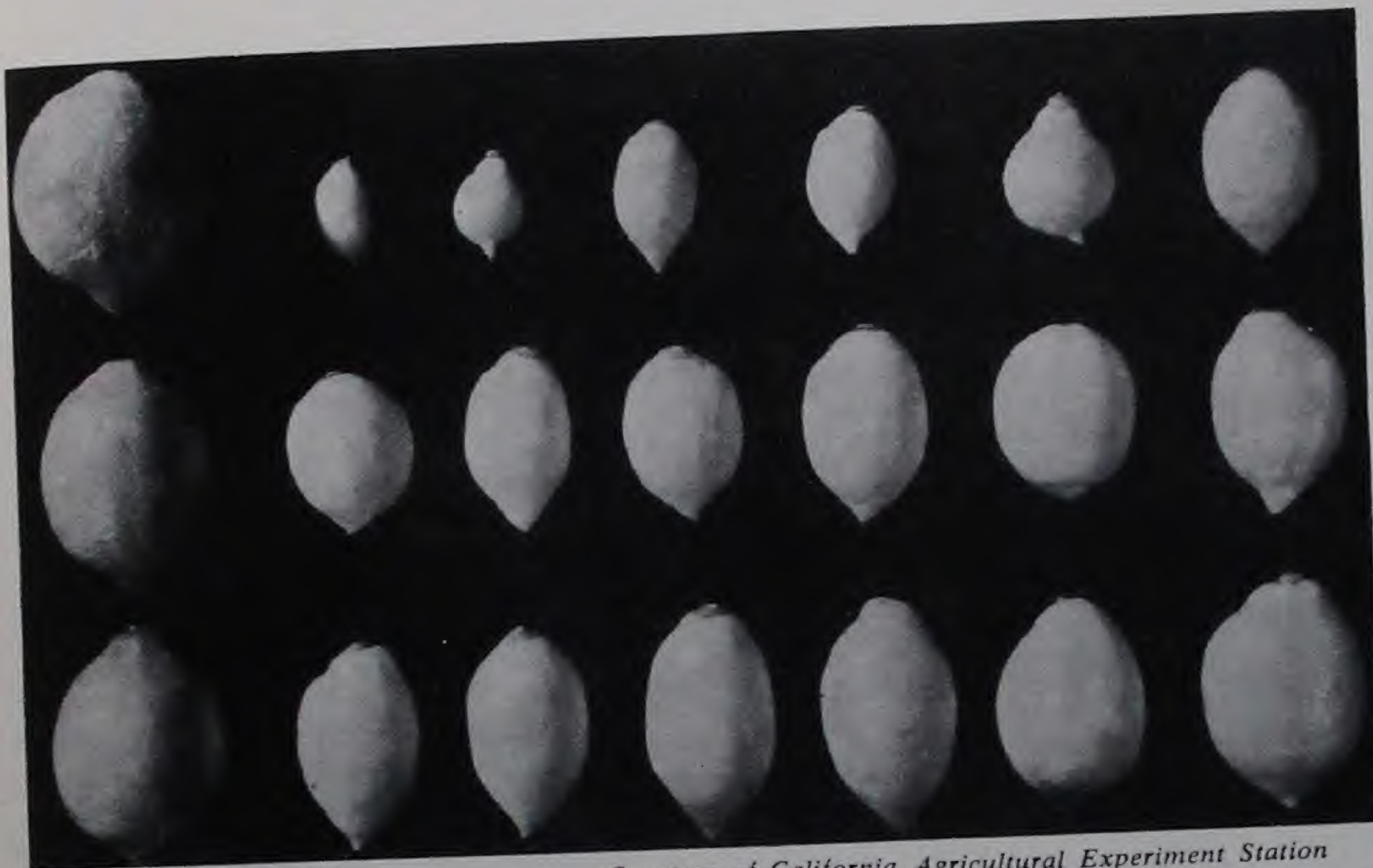
maturely and appear whitish (figures 14, 15). In case of prolonged severe zinc deficiency, the trees go out of production but marked increases in yields result from a correction of the disorder (53, 54).

Zinc deficiency often accompanies other deficiencies, and multiple deficiencies on one tree and occasionally in the same leaf are possible. Multiple deficiencies usually involve two metal elements. Thus, zinc and iron, or zinc and manganese, may both be present in deficient amounts simultaneously and cause complex symptoms that are not easily identified. When one deficiency is corrected, however, the second comes into sharp focus (44).

Citrus trees suffering from virus or fungal disease often show zinc deficiency, whereas healthy adjoining trees are free of symptoms. This may be the result of a weakened root system that is unable to absorb zinc, or it may indicate impaired transmission of zinc through the phloem, the conductive tissues of the plant. Many diseases interfere with normal functioning of the phloem.

Figure 13. Valencia orange tree severely affected with zinc deficiency, showing dieback, small leaves, and very small crop.

Courtesy of California Agricultural Experiment Station



Courtesy of California Agricultural Experiment Station

Figure 14. Normal lemons (left) in comparison with lemons (right) from trees severely affected by zinc deficiency.

HISTORY AND REMEDY

Zinc deficiency probably is as old as the cultivation of citrus. This disorder is found in all citrus growing areas of the world. References to "frenching" appear in the earliest writings on citrus culture in Florida. Little was known as a practical remedy until work in California showed that either soil or foliage spray applications of zinc gave correction (17). Duplication of field symptoms was achieved in zinc-free solution cultures in 1937 (16). Soil-applied zinc generally is erratic and slow in causing response and has not been used widely. Where surface soil applications have been tried, concentrating the zinc salts in a few piles or in a band around the edge of the ground areas shaded by the trees have been more effective than broadcasting (36, 46). Zinc ions do not move readily in the soil because of fixation by soil colloids, especially organic particles, and also are immobilized if the soil reaction is greatly above pH 6. In spite of these immobilizing actions, citrus roots are able to obtain zinc if they come into contact with it. This has been demonstrated in long-term tests where zinc sulfate was plowed-in to a depth where root contact was possible. Even with a pH above 7, citrus trees have been able to obtain sufficient zinc (72).

Most zinc applications on citrus have been foliar sprays applied as deficiency preventatives rather than correctives. Leaf analyses provide an excellent guide for impending deficiencies (82). In actual practice, however, spray applications can be governed by the prevalence of visible symptoms. If no visible patterns are present, sprays can be postponed until a few trees start to show leaf symptoms. This practice in

Courtesy of Florida Agricultural Experiment Station

Figure 15. Acute zinc deficiency symptoms on Pineapple orange (left) showing very small, smooth fruit and pointed leaves with striking contrast in leaf pattern, and (right) fruit and foliage from a similar tree one year after treatment showing immediate resumption of normal growth.

Florida has greatly reduced the frequency of zinc sprays. Orchards that formerly received annual sprays may not need spraying for several years as the roots pick up considerable zinc from accumulations in the soil from past foliar sprays. In some cases, where the soil is heavy and the pH is high, regular sprays must be applied (63). This also is the situation in California where residues of zinc from continued foliage sprays accumulate in the top 6 inches of soil (60). In the desert areas of California, each major flush of growth must be sprayed in order to prevent deficiency symptoms. Very little zinc is translocated from the sprayed leaves to the leaves of a new flush (82). Zinc sulfate, precipi-

tated with lime or soda ash, long has been used as a spray material but a strong tendency has developed for using zinc oxide or other neutral zinc preparations as they leave less residue on the foliage. Minimal spray residue is desirable from the pest control standpoint as heavy residues encourage the buildup of high populations of scale insects and mites.

MANGANESE (Mn) DEFICIENCY

SYMPTOMS

Manganese deficiency seldom is referred to by any other name, although the condition formerly called "marl-chlorosis" apparently was primarily a manganese deficiency or a joint zinc-manganese-iron deficiency of citrus grown on marl or calcareous soils.

Manganese deficiency symptoms originate on young growth but they may persist and be found on leaves of any age. Extremely mild deficiency may not be evident until the leaves are nearly fully expanded. At this stage light green blotches or mottling appear laterally along leaf margins. Such symptoms are transient and tend to disappear in a few weeks. If the supply of manganese is somewhat more scarce, the mottling is more intense and more persistent. Such a condition is illustrated in plate 8. The blotches are a still lighter shade of green than found in very mild cases and are irregular in contour; many of them resemble inverted horse-shoes with the open parts of the shoes facing the midrib of the leaf. Such a stage of deficiency has an indefinite future as it may gradually disappear without corrective measures being taken, it may persist for one or two years and still be present at final leaf drop, or it may become more pronounced. Such leaves, however, seldom go into a severe stage of deficiency.

Severe manganese symptoms are not evident upon shoot emergence, as may be the case with zinc or iron, but as the leaves begin to enlarge rapidly strong mottling patterns develop (figures 16, 17). The pattern consists of a light green to whitish mottle upon a background of broad green veinal bands. Extreme cases may be co-existent with deficiencies of other metals. If iron deficiency is not involved, however, examination of less affected shoots usually affords information for a correct diagnosis. A gradation of degrees of severity is shown for lemon leaves in plate 9. The color contrast never approaches the yellow and green of zinc mottle, and leaf size is not greatly reduced as in the case of zinc deficiency.

Figure 16. Manganese deficiency symptoms on Valencia orange leaves: Mild deficiency showing the lighter green color between primary veins (top). One leaf has recovered its normal color as a result of being painted with a dilute solution of a manganese salt (top right). Severe deficiency symptoms (bottom). The young terminal leaves are light green in color with slightly darker midribs and lateral veins. In leaves of intermediate age, the pale interveinal spaces embrace a larger area and the colors are dull. Older leaves at the bases of twigs are extremely dull and light in color in areas between veins, and many whitish spots have appeared.

Courtesy of California Agricultural Experiment Station

Manganese deficiency symptoms first appear and are likely to be more severe on the shady sides of trees (56). The lower branches on the north or northeast portions are apt to show the only symptoms on trees when the deficiency is very mild. Shaded, inside leaves also are inclined to show mild symptoms while exposed leaves may be entirely free of visible signs (figure 18).

Figure 17. Moderately severe symptoms of manganese deficiency on leaves of the Eureka lemon. The color contrasts are generally greater in individual younger leaves and mature leaves of lemons than in such leaves of oranges. In old leaves the contrast may be less marked in lemons.

Courtesy of California Agricultural Experiment Station

Early defoliation is not associated with manganese deficiency except in very extreme cases (55). Leaves severely affected are generally persistent and may become bronzish in color and develop small brown necrotic spots as described in sand and solution cultures (15, 30). Such a condition is rarely seen in field grown trees.

No fruit symptom of diagnostic value is known. Trees that are severely lacking in normal foliage from manganese deficiency are lowered in production and their fruit may be pale in both internal and external color (4). This response, however, results from almost any weakening influence.

HISTORY AND REMEDY

Manganese deficiency symptoms no doubt have occurred for many decades but no clear reference to the disorder as a separate entity exists in early literature. No doubt, this is because other deficiencies tend to

develop simultaneously, and either dominate or mask the manganese pattern.

The essentiality of manganese for healthy growth of citrus apparently was first shown by Haas (30). Although he did not adequately describe the leaf patterns later recognized as typical, his illustrations of plants grown without manganese show unmistakable manganese deficiency. Field responses of improved tree vigor and better fruit quality were found by Bahrt and Hughes (4) and detailed symptoms were

Courtesy of U. S. Department of Agriculture

Figure 18. Manganese deficiency on grapefruit leaves. Necrotic areas are from freeze injury illustrating greater susceptibility of deficient leaf tissues.

described by Camp and Peech (10). Widespread manganese deficiency symptoms came into sharp focus in Florida in the late 1930's following the correction of widespread zinc and magnesium deficiencies. In California, manganese deficiency may occur simultaneously with deficiencies of zinc and iron and be masked (44).

In the acid soils of Florida, the inclusion of manganese sulfate in fertilizer has largely controlled the deficiency of this element. However, as the pH goes above 6, soil applications lose their effectiveness, and sprays must be used. If soils are rich in manganese, roots obtain considerable amounts by contact even under calcareous conditions. Stirring manganese bearing compounds into the soil by deep plowing may be effective even with the pH above 7 (72). In general, however, annual sprays are required on most calcareous soils.

Spray applications of manganese sulfate precipitated with lime long have been used with good success in humid climates. They are less effective in arid regions (44). Newly matured leaves will respond in two to four weeks in Florida but old leaves react more slowly and may not show complete loss of symptoms. Finely ground manganous oxide also is effective and is becoming more generally used than the sulfate form because less residue is left on the foliage. Some difficulty has been encountered in removing the residue from fruit at harvest time. The growing tendency is to use manganese in a nutritional spray only when necessary. This means in practice that some orchards are never sprayed with manganese, some only occasionally, and others fairly regularly—all depending on the incidence and persistence of foliar symptoms. In California, the correction of mild, persistent manganese deficiency has increased yields (44).

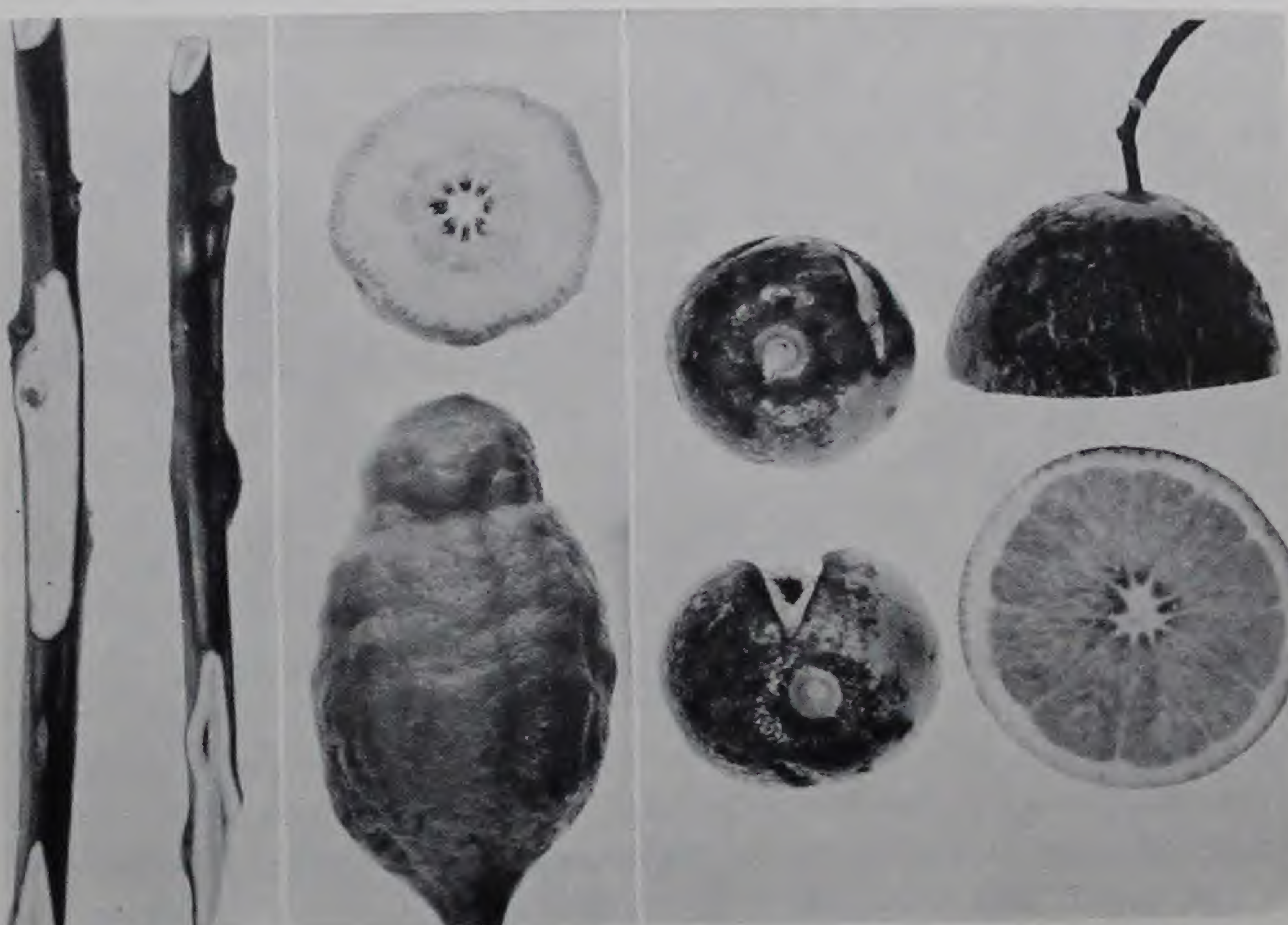
COPPER (Cu) DEFICIENCY

SYMPTOMS

Copper deficiency symptoms are variously called "exanthema," "red rust," "ammoniation," "dieback," "multiple bud," or "peach leaf condition." Unlike shortages of other heavy metals, copper deficiency is not associated with a leaf chlorosis in citrus. The earliest symptoms generally are found on trees that are growing vigorously but do not have sufficient copper to accommodate the new tissues. Such trees are prone to develop a few long vigorous shoots with large leaves rather than a large number of medium length shoots with leaves of usual size. At first these large leaves may become very dark green and give the impression of unusually good health and vigor. Shoots that develop laterally may show a phototropic (light) response by turning upward at their outer ends, giving rise to an S-shaped condition. Early observers in Florida placed considerable emphasis on this type of growth as an indication of copper deficiency. Such a response may be suggestive of a low copper status, but it is not a specific symptom as vigorous healthy shoots will do the same thing.

Soon after long dark green shoots develop, yellowish blotches may appear on them, usually beside or just below the leaf nodes. These areas appear to indicate stoppage in the phloem so that carbohydrates cannot move from the leaves into the tree. The blotches on a typical copper deficient stem enlarge until one or more of them completely surrounds and girdles it. Small swellings or "bumps" frequently de-

velop along the stem simultaneous with the yellowish blotches (plate 10 and figure 19). When these swellings are punctured, a brownish gum may be seen, or it may ooze out. These gum pockets are in the bark and they may rupture and glaze the outside of the twig with a reddish brown exudate. This excretion is water soluble and may be washed away by rain in which case the ruptured "bump" may appear dry and free of gum.



Courtesy of California Agricultural Experiment Station

Figure 19. Copper deficiency: Sucker growth showing gum blisters and gum pockets (left). Young lemon fruit showing gum pockets around central pith and rough exterior (left center). Mature orange fruit showing gum excretions on rind and splitting tendency (right center). Mature orange showing scabby, reddish brown, cracked rind, gum pockets around central pith and semi-gelatinized juice vesicles (right).

With time, the leaves become yellow veined (a girdling symptom) and drop off leaving a bare yellowish or brown stained twig which soon dies back to the point where the shoot originated. Several buds then may attempt to grow out from the site of the original bud giving rise to a "multiple bud" condition. In contrast to large original leaves, the leaves on these multiple shoots are small and abnormal in shape and color. They may be quite narrow and elongate with very rough margins and a dull brownish green color. Such leaves superficially resemble peach

leaves and the affliction was at one time referred to as a "peach-leaf" condition (26). This type of growth may persist for a considerable length of time but if the copper status is sufficiently low these small shoots will go through the same process of gumming, leaf dropping, and twig dieback as did the original. Such a condition is shown in plate 11.

If the copper deficiency persists over a period of years, larger branches die back and the tree actually shrinks in size. Large leafed sprouts may then develop from the large limbs or trunk (figure 20) and these shoots

Courtesy of Florida Agricultural Experiment Station

Figure 20. Pineapple orange tree affected with acute copper deficiency showing dying back of new growth and very large foliage on water shoots (left). Tree of same age and same fertilizer treatment except that it received applications of copper sulfate (right).

gradually go through the dieback process previously outlined. Trees suffering from acute copper deficiency are easily damaged by frost and many dead branches may result from that cause. Severe and prolonged copper deficiency, however, can be lethal, as gumming will eventually develop in the trunk bark and even the bark of the larger roots.

Side by side and under the same cultural conditions, orange trees are more readily damaged by copper deficiency than grapefruit, and tangerines are even more tolerant (plate 12). These observations were

readily apparent many years ago in Florida when copper deficiency was widespread.

When only mild copper deficiency exists, orange fruits may develop normally or some may be marked by a reddish brown stain which appears to result from eruptions of gum which accumulates in the outer layers of the peel. These may be only scattered specks in mild cases, they may form spots one-eighth inch in diameter, or they may overlap to form large dark brown areas on the fruit (figure 19). This peel blemish is much less likely to appear on grapefruit than on oranges and is very rare on tangerines.

When copper deficiency is acute, young orange fruit may develop this peel discoloration at a very early age, become misshapen, and be shed early. The few that remain may not develop properly, be low in acidity, insipid in taste, and have pulp which dries out early in the maturing season. Such fruits may develop gum along the inner edges of the segments facing the fruit axis (figure 19). Because the affected areas of the peel become rigid, splitting of such fruit is common at all stages of development including both longitudinal splitting from the stylar end and transverse splitting in brown areas of gum excrescence (figure 19).

Spotting of the peel of grapefruit is less frequent than in oranges and the affected surface areas are more sharply defined when they appear. Gum pockets may be found in the albedo (white tissue) of grapefruit but rarely in the center of the fruit (5).

HISTORY AND REMEDY

Unmistakable symptoms of copper deficiency were described by Florida growers prior to the Civil War (84). Both soil applications of "bluestone" and bordeaux sprays as remedies appear to have been used by growers prior to 1900 in Florida but general acceptance of the use of copper compounds was delayed until about 1920. In 1913 Floyd reported (25) successful results from experimental bordeaux sprays and in 1916 Grossenbacker demonstrated (28) responses from soil applications of bluestone. This was a number of years before the establishment of copper as an essential element for green plants. Laboratory confirmation of the essentiality of copper for citrus was not achieved until 1935 (33).

Virtually all virgin citrus soils in Florida are deficient in copper. The need can be met with a single application of 10 to 30 pounds of actual copper equivalent (Cu) per acre worked into the soil (72), or through

the use of sprays containing copper. Older orchards have accumulated toxic quantities of copper from continuous use of soil and spray applications (65). Where copper is used in fungicidal sprays, the physiological requirements of the trees are amply met without any being applied to the soil (63). Bordeaux-type sprays are now largely replaced by copper oxides.

In other citrus areas, where soils are heavy, spray treatment is much more efficient than soil applications. Copper deficiency has been found in some areas of California for many years but preventative measures are not as universally practiced as in Florida.

IRON (Fe) DEFICIENCY

SYMPTOMS

Iron deficiency is known simply as "iron chlorosis" or as "lime induced chlorosis." It is known throughout the citrus growing areas of the world and probably occurs second in prominence only to zinc. It develops on young growth but may persist throughout the life of leaves.

In mild cases young leaves become pale green except for the veins and small veinlets which remain dark green. This causes a ribbed or feather-like appearance (plate 13 and figure 21). As the leaf continues to enlarge it becomes unusually thin and semi-transparent. Leaf size frequently is somewhat reduced but not as drastically as in the case of zinc shortage. Mildly affected leaves generally recover as they mature and sufficient iron is accumulated. Thus, the netted pattern is not uncommon on terminal shoots of new growth while older leaves appear normal.

In cases of moderate severity, the netted pattern still may be present while the entire leaf appears yellowish orange. The thin lines of green along the veins are almost invisible. The disorder is evident in very young leaves and persists long after they have matured. Leaf size generally is reduced noticeably but conformation is unchanged for the species involved. As in mild cases, leaves are noticeably thin and paper-like. Such leaves are persistent and may remain on the tree for a normal life span of one to three years. With extended time the leaves gain some greenness but seldom recover completely without special treatment.

In severe cases, the symptoms are drastically accentuated. Newly emerging leaves may be almost white with only a faint tinge of green along their midribs. They seldom enlarge to full size. They may change

from white to netted green as some iron finds its way into them (figure 22). Leaves so severely deficient in iron, however, are very fragile and they may develop necrotic spots and drop off at an early stage. New growth is sparse and iron deficient trees tend to die back,

Figure 21. Iron deficiency symptoms on orange showing fine venation on young leaves and spotted response to iron spray on older leaves.

Courtesy of California Agricultural Experiment Station

especially on their sunny sides. Over a period of years severely affected trees decrease in size from the dying back of twigs and small branches.

As with zinc and manganese, a very mild deficiency of iron does not noticeably affect the yield or quality of citrus fruit. With increasing severity, however, tree performance is hampered until, in severe stages, the tree is almost fruitless. In this case, the few fruits borne are small, hard, coarse, dry, misshapen, and very pale in color.

HISTORY AND REMEDY

Iron chlorosis is one of the oldest recognized ailments of plants and for some, such as citrus trees, no completely successful method has been found to remedy the problem. Iron sulfate has been used as a fertilizer material in Florida by some growers since about 1900. Doubts may be raised whether such a practice has benefited the trees as even massive applications on acid soils have failed to correct even

Courtesy of California Agricultural Experiment Station

Figure 22. Iron deficiency symptoms on lemon leaves.

mild deficiencies when tried experimentally (63). Iron sprays have been tried extensively with unsatisfactory results. At best only a speckled greening of the leaves has been achieved (figure 21). Injections of ferrous sulfate are effective but not practical because of only temporary recovery and injury to treated trees (77).

In the past decade, chelating materials have been tried extensively since the discovery by Stewart and Leonard that trees on acid soils respond quickly to small applications of Fe-EDTA (iron chelate) (80). Chelates are complex organic compounds which carry metal elements in a relatively soluble form, available for absorption and use by plants. Iron chelates have provided a practical remedy for acid soils but chlorotic trees on calcareous soils still are a serious problem. Sprays

of chelated iron are not effective and soil applications are unpredictable under conditions of high pH. The required quantities of chelates are uneconomical generally, but some materials, such as HFeEDDHA, frequently are effective. This material often will green up some trees in an orchard and not others. Even those trees that respond are inclined to require rather frequent retreatment, thus maintenance is costly. A survey of progress in study and use of chelating agents was recently published by Wallace (87).

Leaf symptoms of iron deficiency became widespread on the acid, sandy citrus soils of Florida about 12 to 15 years ago. Detailed study showed that toxic accumulations of copper in the soil was responsible. Most generally, heavy applications of lime restored tree vigor and the chlorosis disappeared. Applications of chelated iron were not essential but their use hastened tree response. While some metal antagonism may be involved, the main effect of the copper apparently was to kill roots. The lime applications inactivated the copper to the extent that absorbing roots could reoccupy the soil. The restored roots absorbed sufficient iron despite the increased pH, a condition which indicates that simple iron deficiency was not involved (65).

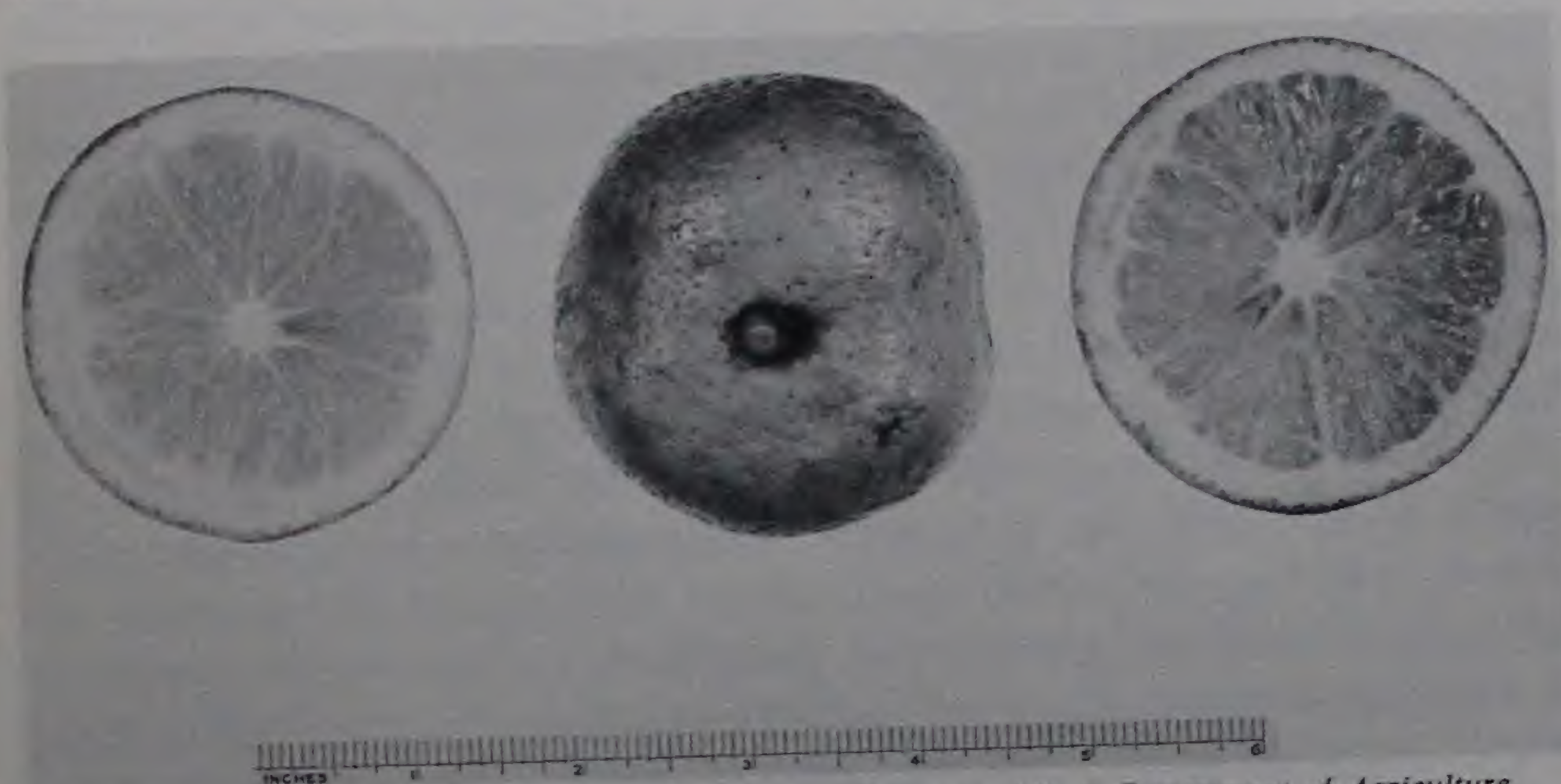
BORON (B) DEFICIENCY

SYMPTOMS

Foliar symptoms of boron deficiency are rather general or nonspecific. Doubts arise whether a positive diagnosis of boron deficiency could be made without leaf analysis or without finding fruit symptoms. A variety of foliar symptoms have been described but they are mostly consequences of general weakening of the tree and vary greatly from place to place. A tendency to wilt easily, drab foliage color, buckling of leaves, yellow veins, corky veins, thickened leaves, puckering along the midrib, and small translucent spots on the leaves, all have been described by one worker or another (31, 32, 50, 67, 69, 74). One or more of these symptoms may be suggestive of boron deficiency but confirmation is required from other evidence.

As shown by Haas and Klotz (32) boron deficiency injures phloem or conducting tissue. Thus, in effect, an internal girdling is caused. Some of the foliar symptoms are the same as those found following mechanical girdling of trunks or branches. Some virus diseases also interfere with carbohydrate movement (principally sugars) and cause symptoms similar to severe boron deficiency. This interference in

carbohydrate transport resulting from boron deficiency starts in the small twigs, causing excess carbohydrates to accumulate in the leaves and fruit and allowing insufficient amounts to go down to the roots. The consequence of this condition is a tree of low vigor. Vegetative growth is sparse, bloom may be excessive, a nitrogen starved appearance may develop even though the supply of nitrogen is plentiful, the tree wilts easily even when soil moisture is available, and the various leaf symptoms already mentioned develop in chronic cases.



Courtesy of U. S. Department of Agriculture

Figure 23. Boron deficiency in mature navel orange fruit. Note uneven thickness of peel, gum in albedo of cut fruit, and lumpy contour of center fruit. Gum deposits in the inner tips of the locules are rare which serves to distinguish boron deficiency from copper deficiency.

As a consequence of the disturbance of carbohydrate metabolism, gum forms readily. Gumming of twigs (31, 70), gum exudate from fruit pedicels (67) and gum impregnation of fruit all have been noted. In fact, the best diagnostic symptom is gumming of fruit (plate 14). Orange trees mildly deficient in boron may not be easily recognized except from fruit symptoms (69).

Fruit of all ages may show symptoms. In the case of young fruit, the green color tends to fade in large areas and the fruits shed excessively (50, 69). They may be lop-sided or lumpy and have large gum pockets in the albedo (white tissue) layer of the peels, just under the lumps. Sometimes a ring of gum completely around the albedo can be found in mid cross-section (figure 23). More typically, however, the gummed areas are scattered in the albedo. The central core, or pith,

may be gum soaked and the seeds may abort and turn dark. If symptoms are very scarce, the albedo in the vicinity of the stem attachment is somewhat more likely to show gum spots than elsewhere.

Unfruitfulness is one of the characteristics of boron deficiency. Many fruits set but fall off in the first three or four months. The few that persist are insipid and low in juice content. They tend to shrivel and mummify on the tree; thus, the name "hard fruit" is descriptive of the problem (50).

HISTORY AND REMEDY

Haas first induced boron deficiency in citrus in artificial cultures (29). Morris first recognized and corrected boron deficiency in the field in Rhodesia (50, 51). Later studies were made by Chapman and Kelley (13), Haas (31), Roy (67), Smith (69), and Smith and Reuther (74, 75). Arsenic induces boron deficiency symptoms as shown by Roy (67). Use of arsenic to lower the acidity of grapefruit sometimes causes mild fruit symptoms as described by Camp (8), but use of boron in fertilizers has practically eliminated such occurrences (63). Boron deficiency in commercial orange orchards in Florida was described by Smith (69) and Smith and Reuther (74). Boron deficiency is not a problem in the United States except in Florida. Most of the irrigation water used in western states contains ample to excess quantities.

Most citrus orchards in Florida now receive boron annually as borax either in mixed fertilizer or in spray. Foliar absorption has not been proven and quite possibly the borax washes off in rain water and is absorbed by the roots. In any case, the amount required per acre is small and varies from 3 to 10 pounds of borax per year. Larger amounts have not been found to be beneficial (70).

MOLYBDENUM (Mo) DEFICIENCY

SYMPTOMS

Molybdenum deficiency long has been known as "yellow-spot" or "orange-spot" in Florida although the cause was not understood until 1951. Unlike shortages of other heavy metals, molybdenum deficiency is unknown in immature foliage. After deficient leaves are fully enlarged and three or four months old, they begin to develop translucent spots along their sides. These spots are light green and relatively inconspicuous unless viewed with transmitted light. They are irregular

in contour and size and resemble during mid-summer another condition known as "mesophyll collapse," collapse of leaf tissue between veins. During the fall the affected areas become impregnated with a resinous gum which extrudes through the lower surfaces of the leaves and makes reddish brown spots. The mesophyll around these spots loses its chlorophyll and forms yellow or orange halos around the gum-soaked areas.

In mild cases only a single spot may appear on a single leaf and only a few leaves may be affected per tree. On grapefruit the spots are typically large, often being one-half inch or more in diameter. The spots are fairly small on mandarins, usually being less than one-fourth inch across and usually slightly elongated between two diagonal veins. Orange leaves show a variation in spot size but spots on them usually are about one-fourth of an inch across or slightly larger. Mild cases may continue to show symptoms for many months. Like signs of manganese deficiency they are inclined to develop first on the shaded sides of trees.

As the severity of molybdenum deficiency increases, more leaves are affected and the number of spots per leaf increases (plate 15). Leaves even may show over-lapping of spots as the number goes up. Usually the spots are most readily seen in late summer or early fall. Leaves that show spots generally are destined to drop early. Thus, leaves produced in spring are dropped in the fall when only eight to ten months old and deficient trees assume a very thin and unthrifty appearance.

While all cultivated citrus varieties appear to show similar foliage symptoms of molybdenum deficiency, none seem to show destinctive fruit symptoms. Yields may be adversely affected in cases of chronic defoliation but quality of fruit is not visibly affected. Trees grafted onto grapefruit rootstocks are more susceptible to this deficiency than trees on other commonly used stocks.

HISTORY AND REMEDY

While yellow-spot or molybdenum deficiency symptoms have been seen in Florida for over 60 years (24), relatively little damage has been done to commercial fruit production by their presence. For unknown reasons, the symptoms have tended to go through cycles. Fairly widespread signs during one year have been followed by several years when symptoms have been relatively rare. Poorly drained soils around lake margins tend to be highly acidic and here yellow-spot has been

most frequently found. Groves that have received considerable ammonium sulfate also have been more inclined to show symptoms.

In 1951 Stewart and Leonard showed (79) that yellow-spot was a specific symptom for molybdenum deficiency. Affected leaves respond to a foliar spray in two to four weeks. As little as 1 ounce of sodium or ammonium molybdate in 100 gallons of water is highly effective. The yellow spots will disappear from the upper surfaces of leaves but the gum spots on their lower sides will remain. Leaves that are sprayed before leaf fall begins generally will regreen and remain on trees for a normal life span.

Yellow-spot symptoms on citrus in Florida now are recognized as an indication of inadequate liming and low soil pH. The symptoms gradually disappear following lime applications and they rarely are found since liming has become a general practice (63). Leaf requirements for molybdenum are very small (85) and phosphatic fertilizers carry significant amounts of this element as an impurity. Widespread molybdenum deficiency in citrus is unknown outside of Florida.

KEY TO NUTRIENT DEFICIENCY SYMPTOMS OF CITRUS

Element Deficient

A. Symptoms originating on young leaves or twigs.
- B. Leaves uniform in color over entire area, growth reduced, frequently resulting in bushy appearance.
  - C. New leaves pale green to yellow, growth short, sparse; trees unfruitful, fruit pale in color.......... Nitrogen
  - C. New leaves very light yellow-green to yellow, markedly yellower than above.......... Sulfur
  - C. New growth repressed, foliage color drab or lusterless, leaves misshapen; fruit with gum spots in the rind, abortive seeds; fruit drop excessive.......... Boron
  - C. Leaves nearly normal, growth willowy and compressed; fruit small, thin skinned, tends to drop prematurely.......... Potassium
  - C. Leaves usually large and very dark green, gum pockets at bases of petioles on vigorous growth, gummy excrescences on twigs and fruit and in axes of fruit segments; dieback of twigs; multiple sprouts.......... Copper
- B. Leaves irregular in color patterns.
  - C. Leaves greatly reduced in size, pointed or very narrow, with sharply contrasting pattern of bright yellow mottling on green background; fruit small and pale.......... Zinc
  - C. Leaves approximately normal in shape and size, or only slightly reduced in size.
    - D. Pale green or grayish mottle on green background; mottle often horse-shoe shaped with open end toward midrib; or may be a marbled pattern with dark green following crooked network of veins.......... Manganese
    - D. Fine network of straight green veins on very light green to yellow or whitish background forming a feather-like pattern, growth reduced, and dying of twigs common.......... Iron

A. Symptoms originating on mature leaves.
- B. Fading of chlorophyll starting in localized areas and gradually spreading.
  - C. Fading of chlorophyll starting laterally parallel to midrib and spreading from there, but with base of leaf usually remaining green in very advanced stages, forming a green wedge; early defoliation of old leaves.......... Magnesium
  - C. Fading of chlorophyll along edges of leaf and gradually involving areas between veins, early abscission of leaves.......... Calcium
  - C. Fading of chlorophyll in blotches at or near the apex or outer half of leaf, blotches spread and coalesce, color deepens from pale yellow to golden bronze, browning of leaf tips, leaves persistent; drab foliage, excessive wilt.......... Potassium
  - C. Fading of chlorophyll in large inter-veinal spots, spots with yellow or orange halo and may coalesce, brown gummy spots on lower surface.......... Molybdenum
- B. Fading of chlorophyll not localized at start.
  - C. Leaves fading to yellow green and eventually becoming entirely yellow or with whitish veins.......... Nitrogen
  - C. Leaves fading to dull green and eventually to orange yellow; in extreme cases, burned areas on leaves; fruit coarse and spongy with hollow center and high acid.......... Phosphorus

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Courtesy of California Agricultural Experiment Station

Plate 1. Orange leaves showing yellowing due to nitrogen deficiency.

a b c d

I

II

a b c

Courtesy of the University of Calif. Agricultural Experiment Station

Plate 2. Effects of varying potash supply on size and texture of oranges. I. Valencia oranges picked in October 1943: a, Fruit picked from trees suffering from acute potassium deficiency. The stems died back on some of these, leading to necrosis of stem and fruit. b, Fruit from tree only slightly deficient in potash. c, Fruit from tree receiving ample potash. d, Fruit from tree receiving excessive potash. II. Navel oranges picked in 1944: a, Fruit from acutely potash deficient tree. b, Fruit from tree only slightly deficient in potash. c, Fruit from tree receiving ample potash. Hilgardia, Vol. 17, p. 650.

Courtesy of California Agricultural Experiment Station

Plate 3. Leaves showing so-called vein chlorosis, a result of girdling of the trunk, rotting of the root, or any other injury that disrupts transfer of plant food in citrus trees.

Courtesy of California Agricultural Experiment Station

Plate 4. Advanced stage of calcium deficiency on lemon leaves showing dead areas developed in mesophyll regions.

Courtesy of Florida Agricultural Experiment Station

Plate 5. Magnesium deficiency in grapefruit foliage showing yellowing of leaves adjacent to fruit. The yellowing starts near the midrib and gradually spreads outward until it takes in the entire leaf, after which the leaf sheds, frequently leaving the fruit on a long twig entirely devoid of leaves.

Courtesy of California Agricultural Experiment Station

Plate 6. Shoot from navel orange tree in early stages of sulfur deficiency. New growth is very yellow as compared with older growth. Yellow leaves are similar in appearance to nitrogen starved leaves. In a more acute stage of deficiency, the older leaves are less green than those shown here and many have a yellowish midrib. These symptoms are from trees grown in large containers of soil. Sulfur deficiency has not been identified in the field.

Courtesy of Florida Agricultural Experiment Station

Plate 7. Zinc deficiency symptoms show dark green coloration along the midrib and main lateral veins with tissues between veins a light yellow. Note that the leaves are narrow and pointed and growth is very fine and upright in character. This gives the tree a bushy appearance.

Courtesy of Florida Agricultural Experiment Station

Plate 8. Manganese deficiency symptoms of newly matured orange leaves, showing dark green areas along midribs and main lateral veins and light green areas between veins. Note that the leaves are normal in size and shape. Such leaves become very dull green at full maturity.

Courtesy of California Agricultural Experiment Station

Plate 9. Symptoms of manganese deficiency in lemon leaves: Very mild symptoms shown by the leaf on the left are commonly seen in the field, but those on the other three leaves are seen occasionally.

Courtesy of California Agricultural Experiment Station

Plate 10. Copper deficiency on "water-sprout" type of vigorous shoots of Washington navel orange. Upper—Intact pustule at base of petiole. Lower—Pustules sectioned to show gum. Pustules may occur singly (upper) or in pairs (lower). Such pustules are specific for copper deficiency.

Courtesy of Florida Agricultural Experiment Station

Plate 11. Copper deficiency in citrus showing large leaves with weak twigs growing from multiple buds which die back before they are fully developed.

Courtesy of Florida Agricultural Experiment Station

Plate 12. Copper deficiency in Pineapple orange showing brown excretions on the surface of the fruit. Such fruits also are likely to have gum pockets in the rind and gum in the axes of the segments.

Courtesy of Florida Agricultural Experiment Station

Plate 13. Iron deficiency symptoms in orange leaves showing fine green veins on a yellow green to yellow background and fine twig growth.

Courtesy of U. S. Department of Agriculture

Plate 14. Boron deficiency in Pineapple oranges. Degreening as shown and excessive shedding of young fruit are associated with this deficiency. Note gum deposits in albedo. Fruit also shows gum in central axis and aborted seed.

Courtesy of U. S. Department of Agriculture

Plate 15. Molybdenum deficiency in grapefruit leaves. Note indiscriminate occurrence and variation in size of yellow spots. Leaf on left shows reddish gum spots on under surface of leaf.

Chapter XII

Nutrient Deficiencies in Sugar Crops

By W. R. Schmehl and Roger P. Humbert *

NUTRIENT deficiencies in sugar beets and in sugarcane must be considered in relation to both yield and quality factors since these crops are grown for the sucrose that can be obtained through processing their respective roots or stalks. Quality factors of concern include not only sucrose content but also purity of extracted juices. Purity is one of the factors which determines the efficiency of crystallization. Thus, fertilizer practices that give high yields may produce a crop so poor in quality that its processing is uneconomical. Conversely, those practices giving a high content of sugar may result in efficient processing, but yields may be so low that the crop is unprofitable for the farmer. The objective in efficient sugar crop production is to provide a balance in soil and crop management practices that will result in high yields and high crop quality.

Symptoms of nutrient deficiencies in the sugar crops have a double meaning: (1), the relationship of the deficiency to yield and (2), the relationship of the deficiency to quality of crop. Both must be considered when interpreting deficiencies of plant nutrients for sugar crops in terms of soil management practices.

PHYSIOLOGY OF SUGAR ACCUMULATION

To understand the nutrient relationships in sugar crops, the physiology of growth in relation to sugar accumulation should be reviewed. This is significant because yield of refined sugar rather than simple dry weight production is basic to the growing of both crops. Quality is of greater importance for sugar crops than for most field crops since payment often is scaled by the processor on the basis of sucrose (sugar) content.

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* W. R. Schmehl is Professor of Agronomy, Colorado State University, and Roger P. Humbert is Western Director, American Potash Institute.

SUGAR BEETS

The sugar beet, *Beta vulgaris* L., is a biennial that develops a large succulent root in which food reserves high in sugar are stored during the first year of growth. The flower and seed are produced during the second year. The beet root generally is grown commercially as a source of sugar.

Sugar accumulates in the storage root when the carbohydrates (sugars) produced during photosynthesis in the leaves exceeds the

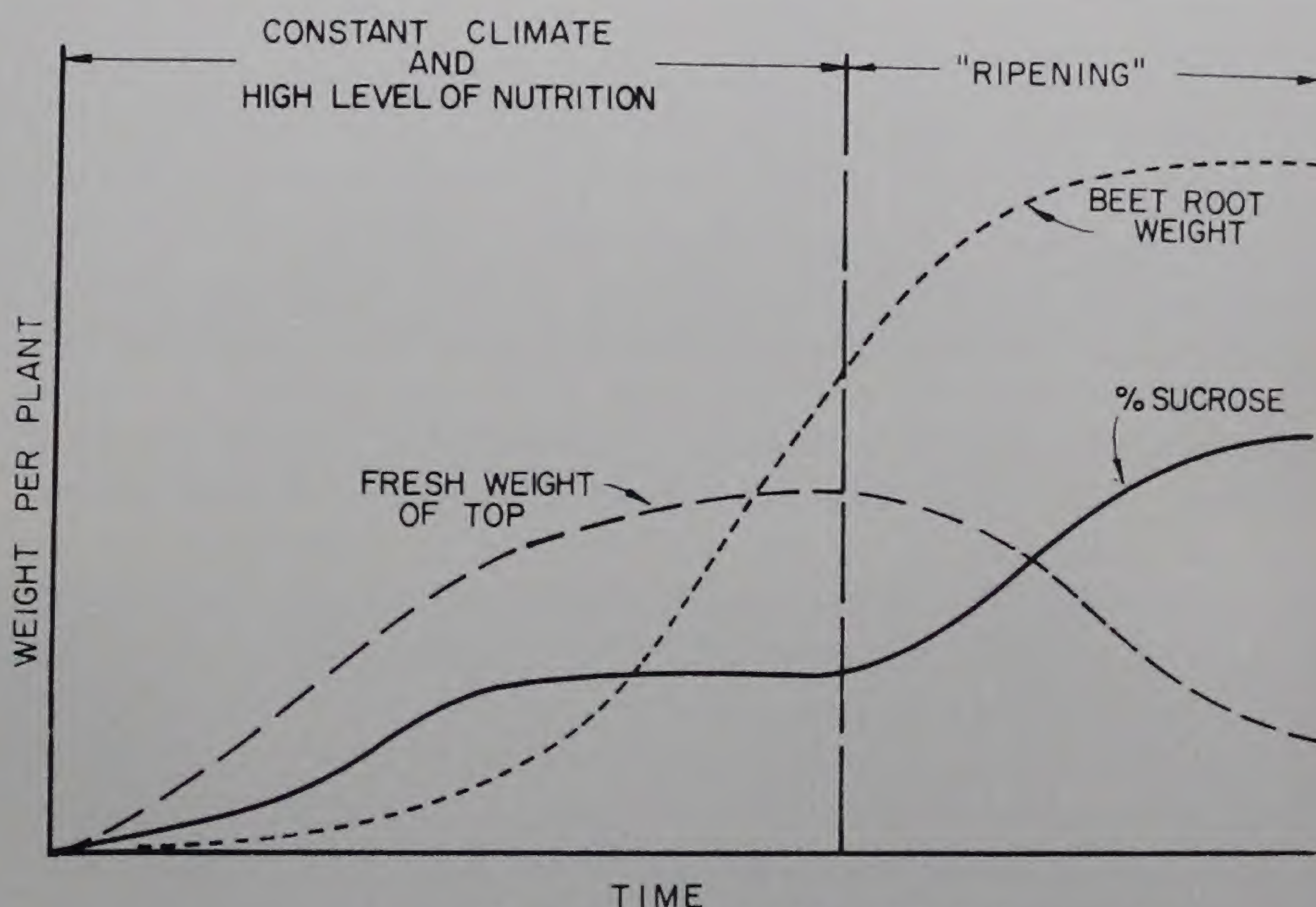

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Figure 1. Schematic diagram of the growth and development of sugar beets during the growing season (left of vertical line) and during ripening.

carbohydrates required for respiration and growth. Carbohydrates are the source of energy for nutrient uptake, nitrate reduction, formation of new tissue, and are a part of new plant tissue. The balance between sucrose used in respiration and growth and that going into storage is not controlled by an internal mechanism that triggers sucrose accumulation; instead, sucrose accumulation is induced by the external environment. When a change in environment induces sugar accumulation it often is called "ripening" or "sugaring up."

Growth and development of the sugar beet and the accumulation of sugar during the season in relation to the environment has been shown

schematically by Ulrich (18) in figure 1. The first part of the season is represented as a time of constant climate and a high level of nutrition. This is followed by a period of ripening caused by cooler temperatures, decreasing nitrogen, or other factors. Early in the season when tops and fibrous roots grow at a rapid rate, sucrose is used largely in growth. Any sucrose in excess of growth requirements is stored in the root. The sucrose content increases slowly. Later in the season the fresh weight of the tops reaches a relatively constant value but the root weight continues to increase while the sucrose content remains nearly constant. The quantity of sugar stored is regulated by that produced minus that used for maintenance and growth. Development of the plant continues in about the same manner until a change in environment causes a change in the pattern of growth of the sugar beet. As fall approaches, cooler temperatures result in slower utilization of sugar in respiration and growth; consequently, sugar storage increases. This is reflected in an increase in percentage of sucrose as the growth rate of the root declines.

The ripening caused by cooler temperatures may be modified by the available nitrogen supply in the soil. If available soil nitrogen remains high, much of the sugar continues to be used in the formation of new plant tissue late into the fall, and the root fails to "sugar up." On the other hand, if the nitrogen supply to the plant decreases as fall approaches, formation of new tissue is retarded, and the sucrose content of the root increases at a faster rate. Maximum sucrose accumulation will result when lower temperatures and nitrogen deficiency are acting simultaneously to induce ripening four to six weeks before harvest.

Under field conditions, air temperatures and amounts of sunlight have considerable influence upon the sucrose contents of sugar beet roots. But since climate is beyond the control of farmers, considerable emphasis has been placed on better soil management practices to improve the quality of the roots. Plant breeders also are working on the problem by attempting to develop new genetic populations which are more tolerant of high levels of available soil nitrogen in given climatic environments.

SUGARCANE

The sugarcane plant, *Saccharum officinarum*, a perennial grass, has been described as the most efficient of all storers of the sun's energy. Sugarcane (figures 2 and 3, plate 10) grows from stools established from

cuttings of stalks. Its growth habits vary with variety, but in general it grows stalks of 8 to 12 feet per year with 3 joints per month. Each stool has a variety of stalks—primary, secondary, and suckers—and has roots, stalks, leaves and tassels.

In most countries the first crop of sugarcane is harvested after 15 to 18 months with each successive "ratoon" crop harvested after 12

Courtesy of Crops Research Division, Agri. Research Service, U. S. Dept. of Agri., Beltsville, Md.

Figure 2. Field of sugarcane at harvest time, Houma, Louisiana.

months of growth. These crops are harvested during the dry season. In some tropical producing areas the cane grows two years between harvests.

Yields of sugarcane vary from 15 tons or less per acre in the lower producing areas to 100 tons per acre. In the lower producing areas, crops are grown on extensive acreages, while in the higher producing areas cultural practices designed for maximum production per acre are followed.

In studies of the physiology of the cane plant, emphasis has been placed on growth as controlled by nutrition, water relationships and climatic factors, and sucrose formation and storage. The cane's root

Courtesy of Crops Research Division, Agri. Research Service, U. S. Dept. of Agri., Beltsville, Md.

Figure 3. A stool of sugarcane at maturity, Newton, Mississippi.

system has been thoroughly investigated and these studies form the basis for fertilizer placement for maximum efficiency of utilization.

Nutrition in sugarcane also plays very important roles in photosynthesis, in sugar synthesis, and in sugar translocation and storage. Studies with radiocarbon tagging show that phosphorus deficiency in the early stages of growth depresses photosynthesis more than does nitrogen or potassium deficiencies. In older plants photosynthesis rates decrease with increasing severity of potassium deficiency. Leaves showing no visible symptoms of potassium deficiency, but having a potassium percentage of 0.91, had a 10 percent lower rate of photosynthesis than control leaves with potassium percentages of 1.70 to 1.89. The rate of photosynthesis in leaves with dry, brown edges and having a potassium percentage of 0.40 was 84 to 98 percent below that in control leaves with potassium percentage of 1.70 to 1.73.

Nutrient deficiencies limit the translocation of sugars to the storage tissues. The downward movement of newly formed sugars proceeds at the rate of approximately 2.5 centimeters per minute in leaves of a well-fertilized cane plant in the field. Phosphorus deficiency does not materially reduce the rate of translocation, nitrogen deficiency shows an intermediate effect, while lack of potassium may reduce the linear rate to well below half that of the control plants.

Growth of sugarcane is very rapid during the first few months after a crop is planted. The cane is fertilized and irrigated for maximum early growth. As harvest approaches, vegetative growth slows down as nitrogen reserves in the soil are depleted. Irrigation intervals are gradually lengthened to force the conversion of reducing sugars to sucrose. In climates with pronounced rainy and dry seasons, growth is rapid during the rainy season and the crop ripens as the dry season progresses. Climatic factors, such as temperature, day length, and others, affect the "sugaring up" of sugarcane just as described for sugar beets.

NUTRIENT DEFICIENCIES IN SUGAR BEETS

NITROGEN (N) DEFICIENCY

A 20-ton beet crop will contain about 200 pounds of nitrogen. In a study conducted in Great Britain, Knowles, et al, (11) reported that about 80 percent of the total nitrogen utilized by sugar beets in a season was absorbed by early July. Similar results were reported by Carlson (4) and Jekic (10). With a crop such as sugar beets which is grown

for its sugar content, high nitrogen fertility is needed early in the season to promote rapid establishment of the plant and to give a large leaf area as early as possible. The plant should, however, become deficient in nitrogen four to six weeks before harvest to induce sucrose accumulation.

If supplies of available soil nitrogen remain high into the fall, top growth continues into the ripening period and the beets fail to sugar up. A very common observation is the inverse relation between the level of nitrogen fertility and sugar content of the root. Excessive amounts of nitrogen late in the season also may cause an increase in soluble impurities which interfere with crystallization of the sugar in refining processes.

Nitrogen deficiency in sugar beets, though desirable during ripening, will reduce sugar production when it occurs early in the growing season. In the spring when the soil is cold and mineralization of organic matter is slow, nitrogen for young beets may be lacking. This deficiency results in stunted plants with small, light-green leaves. As soil temperatures rise, release of nutrients from organic matter increases, and plant roots forage deeper into the soil. In some soils, the plants will green-up and growth will proceed normally; in other soils, those quite low in available nitrogen, the crop may not recover fully without addition of supplemental nitrogen.

Nitrogen deficiency in sugar beets is observed initially as a general light-green color of the leaves caused by the loss of chlorophyll (chlorosis). Since nitrogen is translocated from old to new leaves, chlorosis is more intense on the older growth, but the yellowing generally is uniform over the individual leaf. As the deficiency becomes more severe, the leaves become yellow (plate 1, left) and the outside leaves later die; with extended deficiency new green leaves may grow in a smaller rosette from the center of the crown (plate 1, right). The leaves of nitrogen-deficient plants grow more or less horizontally from the crown so that the old leaves tend to lie flat on the ground (6, 7). When nitrogen is lacking, the photosynthetic area is reduced; nonetheless the sucrose content of the root may be quite high because growth is restricted.

Leaf symptoms of nitrogen deficiency are most easily confused with certain infections, such as virus "yellows." With this disease a general yellowing occurs and an infected field may have the appearance of nitrogen deficiency even though the plants have adequate supplies of this nutrient. Close observation will show, however, a patchy yellowing on individual leaves (9) as contrasted with the more uniform yellowing with nitrogen deficiency. If a question of positive identification arises,

nitrogen deficiency generally can be detected by testing for nitrate-nitrogen in petioles (leaf stems).

Late applications of nitrogen fertilizer are not recommended because new top growth is stimulated and stored sugar may be utilized in respiration and growth. In climates where there is little late summer or fall moisture and evaporation rates are high, nitrate salts may concentrate on the soil surface. Late rains return these surface nitrates to the root zone. This stimulates top growth and reduces the sucrose content of beet roots in a manner similar to late applications of fertilizer nitrogen (16). Nitrogen in organic residues also may become available as soil moisture increases and result in stimulated growth late in the season.

High levels of petiole nitrogen, similar to those caused by excess available soil nitrogen, may be produced by a nutrient imbalance resulting from a deficiency of some other nutrient. When the deficient nutrient is added, the sucrose content of beet roots often increases. On the other hand, when petiole nitrogen is high because of an excess of available nitrogen rather than a deficiency of another nutrient, application of other nutrients in large amounts, for example, phosphorus or potassium, generally has little or no influence on the sucrose content of the roots.

PHOSPHORUS (P) DEFICIENCY

Carlson (4) in Montana, and Knowles, et al, (11) in Great Britain found that phosphorus is absorbed more uniformly throughout the season than is nitrogen. In their experiments, about 50 percent of the total phosphorus in the beet plant was absorbed by August 15. In Ontario experiments by Brown and Irving (3), one-half of the plant phosphorus was not absorbed until about the first of September. Jekic (10) reported that uptake of phosphorus by the sugar beet was greatest in the period 90 to 120 days after emergence.

The pattern of phosphate uptake by sugar beets may explain why they frequently recover from phosphorus deficiencies noted during early stages of growth if this element becomes available later in the season. The large difference in early growth of the beets in figure 4 was caused by a difference in the availability of applied phosphate because of method of application. Visual differences observed in growth in the seedling stage had disappeared by August and final yields were the same on both plots. This will not always occur, however, and results probably would have been different had the plants been attacked by disease or insects

during the early stages of growth. Also, the ability to recover from delayed applications of phosphate without loss of yield will depend upon the severity of the deficiency.

Phosphorus deficiency may delay emergence of sugar beet sprouts, and cause the seedlings to grow slowly and become stunted. Leaves of deficient plants generally are green to dark green (plate 3A) and may be fringed with a bronze or reddish coloration. The leaves of phosphorus deficient plants stand erect. The dark green color is asso-

Figure 4. The effect of method of phosphate application on growth of sugar beets during June. The plot on the right received 110 lbs. P in side band planting; the plot on the left received the same rate of P plowed down 2 weeks before planting.

ciated with a high level of nitrate nitrogen in the plants caused by restricted growth. Since there are no good characteristic symptoms of phosphorus deficiency, petiole analyses are required to confirm diagnosis.

If phosphorus deficiency persists as the season progresses, sugar beet leaves gradually lose their dark green color and may become a light green or yellow (7). Older leaves die and the plant symptoms may resemble those of nitrogen shortage, but a tissue test for nitrate nitrogen will distinguish between the two deficiencies at this stage of development. An acute phosphorus deficiency may cause a brown or black inter-veinal necrosis and the leaves tend to curl upwards. In advanced stages the plant dies leaving a whorl of dead leaves around the crown (9, 14a).

Phosphate deficiency usually is difficult to diagnose early by visual observations and by the time the deficiency is confirmed, crop yields may be reduced considerably. Applications of phosphate after the crop is growing are only partially successful, because phosphorus is strongly absorbed by the soil, and fertilizer is difficult to place in the root zone

without considerable root injury. Since reliable methods of evaluating the level of available soil phosphorus are well known, a soil test should be used to determine the need for phosphorus before planting. When need for phosphate fertilizer is established, it should be applied as a preplanting treatment or no later than at planting.

POTASSIUM (K) DEFICIENCY

A 20-ton per acre sugar beet crop will contain about 200 to 225 pounds of potassium. Potassium is not a structural component of the plants but is associated with growth processes. This nutrient is required in carbohydrate metabolism, and is essential in protein synthesis (21).

Potassium is found in plants largely in soluble form in the cell sap and cytoplasm. When potassium supplies are adequate, it is distributed relatively uniformly throughout the leaves. Concentrations of potassium are highest in the growing points. When a shortage of this nutrient occurs, it is readily translocated from older to newer, more actively growing tissues; therefore, a deficiency of this nutrient is observed first on the older leaves. First signs of potassium deficiency appear as a yellowing at tip and leaf edges (plate 2, second leaf from left). As the deficiency increases, the dull yellowing extends inwards between the veins, the edges turn brown, and a marginal necrosis develops (6). A crinkling of the leaf may develop because growth in its center continues, whereas growth is stopped on the leaf extremities due to deficiency of potassium in that region. With still greater deficiency, the older leaves show an inter-veinal scorch, followed by withering and collapse. Wallace (21) reports that the leaves of potassium deficient plants may be long and narrow with longitudinal lesions on their petioles and midribs.

The scorching of leaf margins which is characteristic of potassium deficiency is not a positive identification. Similar symptoms may develop from magnesium deficiency, burning from excessive soluble salts, drought, or boron toxicity (21). Plant analysis may be required for positive identification.

SODIUM (Na) DEFICIENCY

Sodium generally is not considered an essential plant nutrient, yet it often enhances the growth of sugar beets in the presence of ample potassium (1, 12). The role of sodium in sugar beet growth is not known. It may replace part of the potassium requirements of the plants. Sodium apparently influences water relations in sugar beets and

appears, under some conditions, to increase their drought resistance (21).

Wallace (21) reports that where sodium in the soil is low, the leaves of sugar beets are dark green, thin, and have a dull hue. The plants wilt more rapidly under droughty conditions. The leaves may grow horizontally from the crown in a manner similar to nitrogen deficiency. There may be inter-veinal scorch similar to potassium deficiency.

CALCIUM (Ca) AND MAGNESIUM (Mg) DEFICIENCIES

Calcium is a constituent of cell walls and has an important role in regulating the acidity of the cell. It is not readily translocated from old to new tissue. Consequently, an available supply of calcium must be maintained during growth, and when calcium supplies are limited the new growth is affected first. Deficiency symptoms on beets usually appear as a distortion and downward buckling of the young leaves (plate 3B). As calcium deficiency increases in severity, the leaf blades collapse, blacken and die, leaving petioles with black tip burn (figure 5). At this stage the symptoms may resemble boron deficiency. The older leaves show a marginal scorch (9, 21).

Magnesium is a constituent of chlorophyll; therefore, one of the deficiency symptoms commonly exhibited is chlorosis. Since magnesium is relatively mobile, deficiency symptoms appear first on the older leaves. Magnesium also has a role in numerous enzyme reactions in life processes and is closely associated with energy supplying phosphorus compounds (21). Adequate supplies of magnesium are governed not only by the absolute level of magnesium but by the calcium-magnesium ratio. A large excess of calcium relative to magnesium may induce magnesium deficiency.

Symptoms of magnesium deficiency appear on beet foliage as a patchy, inter-veinal chlorosis beginning near the tips and leaf margins, appearing first on the older and then on the newer leaves. As the deficiency becomes more marked, the chlorosis progresses inward from the margins as large lobes between green veins. In the more advanced stages the yellow areas become necrotic, first near the leaf margins and then extending between the veins (plate 4); the older leaves may wither and drop from the plant. Magnesium deficiency tends to show a more general yellowing of the leaf than does potassium shortage. Magnesium deficiency also may be confused with virus yellows in some stages of development. Virus yellows tend to show a patchy irregular distribution of symptoms over the leaf and the yellow leaves are thick and brittle (9).

Calcium and magnesium deficiencies may appear on plants grown, 1) in soils of intermediate to high soil acidity which have limited supplies of exchangeable calcium and magnesium because of their light texture, or 2) in soils where there is an imbalance among the levels of soil calcium, magnesium, potassium and sodium. In situations where acidity is quite high, possible calcium and magnesium deficiencies in the plant

Courtesy of R. L. Cook, Michigan State University

Figure 5. Calcium-deficient sugar beet. Note the death of the new growth.

often are masked by toxicities caused by excess soluble aluminum and manganese in the soil (15, 21). Aluminum toxicity causes stunted plants with dull green leaves; dead areas may appear near tips and margins of the leaves. Leaves and shoots show symptoms similar to phosphorus deficiency; roots are small and may be sprangled. Symptoms of manganese toxicity appear usually as a uniform yellow-green and the plants are stunted. In later stages chlorotic mottling and necrosis may develop (9, 21).

Calcium and magnesium deficiencies may be so closely associated with soil acidity that deficiencies of these nutrients can be alleviated only by the application of a material such as limestone or dolomite which also

reduces soil acidity. Neutral salts are unsatisfactory sources of calcium and magnesium on strongly acid soils (15).

SULFUR (S) DEFICIENCY

Sulfur deficiency in sugar beets has been reported in California (14) and in Oregon (17). Undoubtedly, this deficiency is not more widespread because sulfur is a constituent of many commercial fertilizers; also, the sugar beet is a deep-rooted crop and sulfur reserves often found in the subsoil become available to the plants. Many of the sugar beet areas in western states are on alkaline soils well supplied with sulfates.

Sulfur is a constituent of proteins and is needed for chlorophyll formation. Symptoms of sulfur deficiency are characteristic in many ways of nitrogen deficiency, since sulfur and nitrogen have parallel roles in protein and chlorophyll synthesis. A deficiency causes a uniform yellowing of the leaves, but since sulfur is not as mobile as is nitrogen, deficiency symptoms tend to be more pronounced on young growth, whereas nitrogen deficiency is most evident in older tissues. As sulfur deficiency becomes more severe, necrotic areas develop which are independent of the veins (plate 5). Petiole analysis can be used to distinguish nitrogen from sulfur deficiency.

BORON (B) DEFICIENCY

Boron deficiency is the cause of a "disease" of sugar beets known as "heart rot," and many attempts were made to isolate the causal organism. In 1931, Brandenberg of Germany found that heart rot was caused by boron deficiency. This has been verified by other workers in the United States as well as in Europe (7).

Boron deficiency in sugar beets has been observed on neutral or alkaline soils of Michigan (7) and in sugar beet growing areas of the Northwest (5, 17). In Great Britain, Hull (9) reports that boron deficiency occurs most often on light textured, sandy soils low in organic matter, and is more common in dry summers. Frequency of appearance increases on limed fields and in heavily fertilized early planted crops.

A deficiency of boron causes a breakdown of the growing point (6, 7). In the early stages of this deficiency, young leaves are distorted and may fail to expand (plate 6, left). Petioles and leaf blades show a transverse cracking which causes a twisting of the petioles and midribs. The older leaves tend to lie on the ground in a manner similar to that caused by nitrogen deficiency, but they are dark green in color until they begin to disintegrate.

In the more advanced stages of the deficiency in a sugar beet, the growing point dies, the outer leaves turn yellow, become scorched, and may die. In severe cases the whole plant may be defoliated. Later in the season, regrowth of leaves, although dwarfed, may nearly cover the black tissue of the crown.

Root symptoms begin to appear during midsummer after the root has obtained considerable size. The deficiency appears first as a grey-brown discoloration of the root tissue and then as a black, dead area in the center of the crown (figure 6). This may result in formation of large amounts of corky tissue and in roots low in sucrose (6, 7). Dark colored pits or holes sometimes develop in crowns (figure 6). Decay of the affected tissue usually results from secondary attacks by fungal organisms (9).

Considerable variability may be seen in amount of breakdown of beet roots. Leaves may show deficiency symptoms with little or no heart rot, but some breakdown of the root generally is noticeable.

Inclusion of boron in fertilizer programs is a general recommendation for beets in Michigan (7) and in other areas where boron deficiency is common. Seven to 10 pounds borax per acre have been found to be adequate in most cases. Boron should be applied in small amounts to prevent toxic effects of too high a concentration, particularly for succeeding crops.

MANGANESE (Mn) AND IRON (Fe) DEFICIENCIES

Manganese deficiencies are most often observed on sandy, light-textured soils that have been limed (7). The cause generally is associated with low availability rather than an inadequate total supply in the soil. Cook (6) advises that the soil reaction should be determined when manganese deficiency is suspected. Under Michigan conditions, manganese deficiency may be expected if the pH of the soil is above 6.8. Manganese becomes highly available in acid soils, and may, in some acid soils, become so soluble that it is toxic to plant growth (15).

A deficiency of manganese is first noticeable as a mottling of new leaf growth and results in a chlorosis of inter-veinal tissue (plate 2, bottom left). The veins and adjacent tissue remain green for a considerable time after the rest of the leaf is yellow. Leaf margins curl upward.

Deficiency symptoms of manganese have been called "speckled yellows" (21) because of the inter-veinal chlorotic mottling. Mottling is rather uniform over the leaf as contrasted with more marginal effects for magnesium deficiency. The mottled areas may develop brownish lesions and the tissue may die and fall out, leaving small holes.

With a more severe deficiency of manganese, the veins may become chlorotic. In such cases, considerable similarity may be seen between manganese and nitrogen deficiency, but the two deficiencies can be distinguished by tissue tests for nitrate nitrogen in the petioles. Manganese deficiency is sometimes confused with potassium as well as nitrogen deficiencies. Deficiency symptoms of these nutrients generally can be

Courtesy of R. L. Cook, Michigan State University

Figure 6. Boron-deficient sugar beet roots. The cross-sectioned beets show blackened tissue and dead hearts with new growth. Note the canker on the side of the whole beet.

distinguished by: (1) an inter-veinal chlorosis for manganese deficiency, (2) a marginal chlorosis for potassium deficiency, and (3) a uniform yellowing for nitrogen deficiency (plate 2).

Deficiency of iron seldom is observed on sugar beets in the field, but it has been produced in sand cultures (7, 21). Since iron is relatively immobile in plants, symptoms in beets appear first on younger tissues as a fine chlorotic mottling or bleaching in contrast to the dark green of older leaves (plate 7). As the plant ages a general chlorosis of the plant may develop.

Symptoms of iron deficiency are similar to those of manganese deficiency, and both deficiencies are to be expected on heavily limed and

alkaline soils. Iron deficiency has been induced in some plants by an excess of other nutrients; for example, when manganese is present in excessive amounts it may cause an iron deficiency; and, conversely, an excess of iron may cause a manganese deficiency (21). If iron deficiency on sugar beets is suspected in the field, a tissue test for manganese, or foliar applications of iron and manganese, may be necessary to confirm the diagnosis.

ZINC (Zn) DEFICIENCY

A sugar beet crop of 20 tons will contain 0.18 to 0.25 pound of zinc per acre. Although only a small amount, this is a relatively large quantity when compared with that needed by other crops. Boawn and Viets (2) surveyed the need for zinc applications on sugar beets in the Yakima Valley and Columbia Basin of Washington. They found, for the most part, little need for zinc bearing fertilizer, but in one case where beets were grown on a sodium soil having a high pH, a 5-ton per acre response occurred following application of zinc sulfate. Lingle and Holmberg (13) observed large yield responses to applications of zinc on slick-spot soils in California and sucrose contents were significantly increased. From tissue analyses, Boawn and Viets concluded that the sugar beet probably will respond to applications of zinc if the young, fully developed leaves contain 10 parts per million (ppm) or less zinc on a dry weight basis. Ulrich (19) found about the same concentration of zinc as the critical level for sugar beets grown in a vermiculite culture.

In its earlier stages, zinc deficiency causes a general yellowing between the veins. This is followed by necrotic spots in the inter-veinal areas or along margins of the younger leaves. In advanced stages of deficiency, the entire leaf blade is necrotic except for main veins (plate 8). Zinc deficiency can be confirmed by analysis of leaf blades.

CHLORINE (Cl) DEFICIENCY

There is little information concerning chlorine as a nutrient for sugar beets. Ulrich and Ohki (20) report that chlorine was required for the growth of sugar beets grown in vermiculite and solution cultures and was associated with sucrose formation. Chlorine deficiency caused reduced top growth and stubby roots.

Foliar symptoms of chlorine deficiency first appear as an inter-veinal chlorosis on the blades of the younger leaves (20). In early stages of development, the symptoms are similar to those of manganese deficiency.

In more advanced stages, smooth, flat depressions form in the interveinal areas and cause the veins to have, by contrast, a distinct raised appearance. In these stages the symptoms are easily distinguished from those of manganese or iron deficiency.

MOLYBDENUM (Mo) DEFICIENCY

Symptoms of molybdenum deficiency in sugar beets have been described in a review article by Hewitt (8). The leaves of an affected plant are small and have a uniform light green color similar to that which occurs in nitrogen deficiency. If deficiency of molybdenum is severe, wilting of leaf tips or petioles results in collapse of the leaves. Margins curl upward to give leaves a cupped appearance. With further development of the deficiency, the leaves scorch and wither, the young leaves blacken, and the growing point dies. This is followed by death of the plant.

PLANT AND SOIL ANALYSES AS AIDS IN DIAGNOSIS

Use of visual symptoms alone to diagnose nutrient deficiencies in sugar beets has certain limitations. For example, some symptoms are not distinctive for a given nutrient; a certain symptom may be visible only after the deficiency is acute, or there may be multiple deficiencies. In addition, environmental factors or disease may cause visual symptoms similar to nutrient deficiencies.

Since nutrient deficiency symptoms may be confounded with each other or with other factors causing similar symptoms, plant analysis has considerable value in diagnosis. Not only can plant analysis help sugar beet growers confirm or identify nutrient deficiencies, it can help them detect deficiency conditions before visual symptoms are apparent.

Ulrich has developed plant analysis into an excellent tool for diagnosing the nutrient needs of sugar beets (19). The basis of his system of diagnosis is determination of the "critical concentration" of each nutrient under controlled conditions. Below the critical concentration of a given nutrient, the plants are deficient in it and the crop will respond to applications. Above the critical nutrient concentration the plants are well supplied with the nutrient and the crop will not respond to that fertilizer element.

Ulrich established critical concentrations for different nutrients in sugar beets in a series of greenhouse experiments covering a wide range in nutrient supply. He found that young, fully matured leaves give the best indication of the nutrient status of the sugar beet plant. Petioles

or leaf blades may be sampled, depending upon the nutrient for which the analysis is made.

Critical concentrations and concentration ranges exhibiting deficiency symptoms in sugar beets for several nutrients are shown in the listing that follows. Comparison of these data with those obtained in tissue analysis of the sugar beet may confirm or disprove visual diagnosis of nutrient deficiencies:

Nutrient	Leaf Part Analyzed	Critical Concentration	Concentration Range Showing Deficiency Symptoms
Calcium	petiole	*	0.04 to 0.10%
Chlorine	petiole	0.4%	0.01 to 0.04%
Magnesium	blade	*	0.03 to 0.05%
Manganese	blade	*	4 to 20 ppm
Molybdenum	blade	*	0.01 to 0.15 ppm
Nitrate nitrogen	petiole	1000 ppm	0
Phosphorus as H_2PO_4	petiole	750 ppm	150 to 400 ppm
Potassium (>1.5% sodium)	blade	1.0%	0.3 to 0.6%
Potassium (<1.5% sodium)	blade	1.0%	0.4 to 0.5%
Sulfur as SO_4	blade	250 ppm	50 to 200 ppm
Zinc	blade	9 ppm	2 to 13 ppm

* Critical concentration not determined.

Soil analysis also will help to identify or confirm nutrient deficiencies, but have their greatest value in predicting the nutrient status of soils before planting. Chemical analysis generally identifies soils low in available phosphorus, potassium, calcium, or magnesium. The soil reaction indicates the possibility of a toxic environment in the soil caused by either excessive acidity or excessive alkalinity. Conversely, soil tests for micronutrients generally are less successful. Examination of the physical condition of the soil may help to establish the cause of certain leaf symptoms.

Successful diagnosis of nutrient deficiencies requires a combination of methods. Partial chemical analysis of plant tissue, as well as an examination of the soil should be used with visual examination to identify and confirm any apparent deficiency. Leaf sprays or soil applications may be required. In some cases, help from a plant pathologist may be needed to distinguish between symptoms caused by a nutrient deficiency and those caused by a disease.

DEFICIENCY SYMPTOMS IN SUGARCANE

NITROGEN (N) DEFICIENCY

As nitrogen becomes deficient, all leaves of sugarcane exhibit a yellow-green color and retardation of growth occurs. Cane stalks

are small in diameter and a premature drying of the older leaves takes place. Roots attain a greater length but are smaller in diameter than those receiving an adequate supply of this element. When nitrogen becomes deficient, vegetative growth slows down and more of the sugars produced are stored. As plants approach maturity, low levels of unused nitrogen are desirable so as not to adversely affect juice quality.

Nitrogen is used in large quantities by sugarcane. At the lower level of nitrogen fertilization, each 75-pound increment of nitrogen results in a sharp increase in both cane and sugar yields. Above 250 pounds of applied nitrogen per acre, the rate of yield increase for cane and sugar levels off and reaches a maximum at 325 pounds nitrogen per acre. At 400 pounds of applied nitrogen per acre, the cane tonnage drops slightly and sugar recovery drops very rapidly, indicating the negative effect of excess nitrogen on juice quality.

Some varieties are capable of using much more nitrogen than others before their juice quality suffers. The potential for increased yields in both sugarcane and sugar beets with some of the newer varieties at high levels of fertilization looks extremely promising.

Timing of nitrogen applications is as important as the amount used. Heavy early fertilization results in a higher proportion of mature primary stalks at harvest while delayed nitrogen application results in larger numbers of immature suckers, causing poorer juice quality.

PHOSPHORUS (P) DEFICIENCY

Phosphorus concentrates in sugarcane plants in the centers of greatest growth activity. High concentrations of phosphorus occur in the meristematic tissues and elongating canes.

Phosphorus deficiency symptoms are characterized by a reduction in the length of sugarcane stalks, diameters of which taper rapidly at growing points. A phosphorus deficient cane stand consists essentially of primary stalks with only a few secondaries and suckers. Such a stand is open and the primary stalks show extremely short internodes after phosphorus becomes limiting to growth. The color of the leaves is greenish blue in contrast with the wide, dark green leaves of normal plants. The leaves are very narrow and somewhat reduced in length. Tillering is markedly reduced and the shoot/root ratio is decreased considerably, even though root development is restricted.

Phosphate fertilization of phosphorus deficient subsoils has greatly increased depth of rooting and increased yields by as much as 3 tons of sugar per acre. The increased availability of moisture and nutrients

because of this increased depth of rooting is particularly important in unirrigated cane in regions subject to drought.

Phosphate fertilizers are applied in seedbed preparation or at planting time to stimulate early root and shoot development. Adequate phosphorus insures an early canopy of cane leaves for maximum growth and photosynthesis. Heavy rates of application often are needed, particularly in laterite soils that "fix" large quantities of phosphorus.

Laterite soils, found in tropical regions, are composed largely of hydrated oxides of iron and aluminum and are reddish to yellowish brown in color. They are unlike soils of temperate zones.

POTASSIUM (K) DEFICIENCY

Plants suffering from a lack of potassium show depressed growth, yellowing and marginal dying of older leaves, and development of slender stalks. An orange-yellow color appears in the older lower leaves which develop numerous chlorotic spots that later become brown with dead centers (plate 9). As the spots merge, general browning of the leaf results. A reddish discoloration which is confined to the epidermal cells develops on the upper surfaces of the midribs. Later, the leaves begin to die back from their margins and tips. This condition of the leaves sometimes is referred to as "firing".

The young leaves of plants deficient in potassium are dark green in comparison with the older, yellowish leaves. Since stalk elongation is slower with potassium deficiency, the young leaves appear to have developed from a common point, giving a "bunched top" appearance.

Potassium deficiencies result in abnormal distribution of water carrying vessels in the pith of roots, small size of vessels and parenchyma cells in stalks, large cavities in the central cortex of roots, and underdevelopment of root hairs.

Potassium is required by sugarcane in amounts greater than any other nutrient. A 100-ton crop of cane removes, on the average, about 450 pounds of potassium per acre. Heavy potash fertilization is commonly practiced, particularly on the acid, highly leached soils of the tropics.

CALCIUM (Ca) DEFICIENCY

The first symptoms of calcium deficiency on the leaves of sugarcane are minute chlorotic spots with dead centers that later turn to a dark reddish brown. The intensity of this spotting increases with the age of

the leaves until the older leaves have a "rusty" appearance. Growth of affected plants is retarded, they become weak, and their stalk rinds become soft. Eventually growth is completely stopped, and the plants die.

Calcium is found in highest concentration in the meristematic tissues and in the younger leaves. It is essential for cell wall development and for the structures that bind the cells together.

Liming is commonly practiced in many sugarcane producing countries. Lime raises the pH of the soil, reducing possible toxicities of iron, manganese, or aluminum; it makes phosphorus and molybdenum more available; it often improves the physical condition of the soil; and it enhances the growth and development of the microbiological populations in the soil.

Sugarcane is grown on a wide range of soil pH. Cane is a remarkably tolerant plant as regards soil acidity and alkalinity. It grows well in acid soils of pH 4.0, as long as approximately 200 pounds of exchangeable calcium are available per acre foot. It grows equally well at pH 8.3, or until excess sodium becomes a problem.

MAGNESIUM (Mg) DEFICIENCY

Symptoms of magnesium deficiency in sugarcane are in some respects quite similar to those that appear when calcium is lacking. The young leaves are light green while the old leaves turn yellowish green, these changes becoming more pronounced as the deficiency continues (plate 11). Small chlorotic spots which later turn to dark brown develop on the older leaves. These leaf markings, when numerous, merge and give the older leaves a rusty appearance. The spotting is most pronounced on the older leaves and decreases in severity as it moves up the stalk onto the younger leaves. In severe cases of magnesium deficiency, the leaves are rusty, and the stalks may manifest internal browning. Different varieties develop the rusty appearance of leaf freckling to different degrees.

A 100-ton crop of cane removes approximately 160 pounds of magnesium per acre. Responses to magnesium on sugarcane can be expected where the level of exchangeable magnesium in the soil falls much below 30 ppm, and where leaf sheath and 8 to 10 internode magnesium contents fall below 0.15 percent and 0.05 percent, respectively.

SULFUR (S) DEFICIENCY

Early symptoms of sulfur deficiency suggest those of nitrogen shortage in that the young sugarcane leaves develop a uniform light yellowish-

green color. Later, with sulfur deficiency, the young as well as the old leaves assume a faint purplish tinge which indicates an accumulation of carbohydrates and the formation of anthocyanin, a red-purple plant pigment. The leaves become narrow and fail to attain their full length. Stalk diameters are greatly reduced, elongation is slowed down, and plants are generally stunted.

Sulfur levels in sugarcane soils vary primarily with past fertilization practices, with use of sulfur-containing fertilizers, and with the sulfur contained in the water used for irrigation. Extractable sulfur of the soil ranges from as little as 15 to several thousand pounds per acre foot. Sulfur deficiencies may be expected to occur where fertilizers containing little or no sulfur are used and where irrigation water contains little sulfate. Responses are expected where the extractable sulfur in the soil falls below 40 ppm. Sulfur requirements of sugarcane equal those of phosphorus, 65 pounds per acre for a 100-ton crop.

IRON (Fe) DEFICIENCY

The first symptoms of iron deficiency in sugarcane appear as a general paling of the youngest leaves followed by the development of alternating green and chlorotic stripes extending their full length (plate 14). The normal green color between the small veins first disappears, leaving the green around the large veins only, thus the striped effect. If the deficiency becomes more acute, the striping becomes less conspicuous and the leaves appear more uniformly chlorotic. During these changes in young leaves, the older leaves retain their dark-green color.

In severe cases of iron deficiency, marked contrasts often occur in the leaves wherein the youngest may be entirely white, the intermediates partially green, and the oldest subnormal green. If iron is not supplied, the plants die.

Iron deficiency may occur in sugarcane growing in lateritic soils containing high quantities of soluble manganese and on high pH soils derived from coral and other calcareous parent materials. Iron toxicity occurs where cane is grown under water-logged conditions and where the iron is reduced from the ferric to the ferrous state. Under the latter conditions grey node symptoms appear.

MANGANESE (Mn) DEFICIENCY

Early symptoms of manganese deficiency in sugarcane leaves are characterized by a fading of the normal green color between the vas-

cular bundles followed by the development of definite, pale, yellowish green to white longitudinal stripes (plate 12). The stripes are confined to middles and tips and seldom extend the full length of the leaves as they do in cases of iron deficiency. This difference aids greatly in differentiating the deficiency symptoms of manganese from those of iron. Where manganese deficiency is acute, the chlorotic stripes become white. Reddish brown areas of dead tissue appear, later develop into continuous stripes, and split the leaves longitudinally.

Manganese deficiencies in sugarcane occur where ratios of available iron to manganese in soils are excessively high. Manganese deficiencies have been observed in many sugar producing districts and have been corrected by incorporating a manganese bearing compound into the fertilizer applied to cane fields.

BORON (B) DEFICIENCY

When cane plants are deprived of boron, minute, elongated watery spots soon develop on the young leaves. These markings are parallel to the veins and result in a definite striping. The leaf lesions soon enlarge and manifest sunken areas in their centers. On lower leaf surfaces, minute, elongated, gall-like bodies frequently develop. In mature lesions, the leaf tissue cracks.

Young leaves become narrow, very much shortened, chlorotic, and badly distorted. Growth of an affected plant is greatly retarded and its stalk remains small in diameter. Internal, brownish streaks frequently develop at and slightly below the growing point.

Boron accumulates in the stalk apex indicating a high requirement of boron in the growing point tissues. Boron deficiency symptoms do not develop until the leaf level falls below 1 ppm.

COPPER (Cu) DEFICIENCY

Symptoms of copper deficiency are shown in poor development of cane stools, droopy tops, chlorosis of leaves, and failure of spindles to unroll. The chlorosis is a pronounced striping effect. Affected leaves are wider and softer to the touch than normal and stalks and spindles have a rubbery consistency and can be bent easily without snapping.

Symptoms of copper deficiency occur only after the copper content of cane leaves falls to 3.5 ppm or below. Copper deficiencies have been corrected in Queensland, Australia, by the application of 50 pounds of copper sulphate per acre.

ZINC (Zn) DEFICIENCY

The most characteristic early symptom of zinc shortage in sugarcane is a pronounced lightening of the green color along the major leaf veins (plate 15). In marked contrast to iron and manganese deficiencies, where the striped chlorosis is inter-veinal, lack of zinc produces a striped effect due to loss of chlorophyll along the veins, although the inter-veinal regions also become progressively paler with increasing deficiency. The distinct white line appearance seems to be due to reduced chlorophyll in the vascular bundle sheaths of the main veins. Evidence of veinal necrosis appears when the symptoms in a plant become acute and growth at its growing point finally ceases. Young tillers which emerge are completely chlorotic in severe deficiency and their leaves soon become necrotic from their tips downward.

Zinc deficiency symptoms occur only after leaf composition drops below 10 ppm on a dry weight basis. Zinc deficiency in sugarcane is rarely observed under field conditions.

MOLYBDENUM (Mo) DEFICIENCY

Molybdenum deficiency signs in cane are characterized by yellow streaks in leaf tissues, is confined to fully mature and older leaves, and increases in severity with age of leaf. The streaks are one to three millimeters in width, and vary in length from a few millimeters to a centimeter or more. These streaks are more dense in the terminal half of an affected leaf, decreasing in density towards its base. In the more mature leaves, the streaks develop some reddish pigmentation in their centers which finally degenerates into lesions of necrotic tissue.

Molybdenum deficiency occurs on acid soils. Liming molybdenum-deficient soils usually corrects the deficiency. In New Zealand, 2 tons of lime per acre was as effective as 2 to 3 ounces of sodium molybdate per acre in correcting molybdenum deficiency. Molybdenum deficiency is rarely seen in sugarcane.

CHEMICAL COMPOSITION OF SUGARCANE

The chemical composition of the cane plant is influenced by many factors, and it differs widely among varieties. The amounts of nutrients removed by different varieties may vary by as much as 100 percent. Some varieties are better able to obtain phosphorus and potassium from a given soil than others. These differences usually are attributed to differences in rooting habits.

The composition of the cane plant varies considerably with climate and seasonal effects. This is particularly true of unirrigated cane, grown under conditions of alternating wet and dry seasons in the tropics.

Fertilizers and manure have been used on sugarcane for many years. The various chemical fertilizers are being used on an increasing scale in all producing countries.

CROP "LOGGING" OF SUGARCANE

Changes in plant composition with time during sugarcane growth have been used effectively to determine optimum fertilization rates in Puerto Rico, Louisiana, Florida, and many other sugar producing areas. The objective of such a "log" is to list all the important factors affecting changes in sugarcane physiology, which the plants experience from the time a crop is started until it is harvested, in such a precise and simple manner that the information can be used as a guide for the profitable production of cane sugar.

The cane crop log is a periodic plotting of climatic data, such as sunlight intensities, maximum and minimum temperatures, and growth records of importance to growers. It records nitrogen, phosphorus, potassium, moisture, and sugar levels in the crop as it progresses to harvest. Other factors are recorded where they may be growth limiting, as well as rainfall, fertilization, irrigation schedules, and yield data for current and past crops.

The nitrogen in sugarcane plant leaves 3, 4, 5, and 6 (in a count from top down, the partially unfolded leaf being number 1) should remain above 1.5 and preferably above 2.0 percent during the early months of rapid vegetative growth. Levels should drop to 1.0 percent at harvest. Immature sections of stalks (between internodes 8 to 10) should have <0.25 percent nitrogen for good juice quality at harvest. The critical levels for various nutrients, the range in which deficiency symptoms appear, and the range without deficiency symptoms for sugarcane are shown in the following list.

The "critical concentration" in sugarcane is that nutrient concentration in tissue where growth of plants slows down in comparison with

plants above the critical concentration. A tissue analysis guide to deficient and nondeficient sugarcane plants follows:

Nutrient	Plant Part Numbered from Top Down	Critical Concentration	Range Showing Deficiency Symptoms	Range Without Deficiency Symptoms
Boron	Blades 3, 4, 5, 6,	1 ppm	<1 ppm	2 to 30 ppm
Calcium	Sheaths 3, 4, 5, 6 Internodes 8–10	0.15% 0.06%	0.02 to .1% 0.02 to .05%	0.1 to 2.0% 0.05 to 2.0%
Copper	Blades 3, 4, 5, 6,	5 ppm	<3.5 ppm	5 to 100 ppm
Iron	Blades 3, 4, 5, 6,	*	1 to 10 ppm	20 to 600 ppm
Magnesium	Sheaths 3, 4, 5, 6, Internodes 8–10	0.1% 0.05%	<0.1% <0.05%	0.15 to 1.0% 0.10 to 1.0%
Manganese	Blades 3, 4, 5, 6,	*	1 to 10 ppm	20 to 400 ppm
Molybdenum	Blades 3, 4, 5, 6,	0.05 ppm	<0.05 ppm	0.05 to 4 ppm
Nitrogen	Blades 3, 4, 5, 6, Internodes 8–10	1.0% 0.25%	1.0 to 1.5% <0.2%	1.5 to 2.7% 0.25 to 6.0%
Phosphorus	Sheaths 3, 4, 5, 6, Internodes 8–10	0.08% 0.04%	0.02 to 0.05% 0.01 to .032%	0.05 to 0.2% 0.04 to 0.2%
Potassium	Sheaths 3, 4, 5, 6, Internodes 8–10	2.25% 1.0%	0.3 to 1.5% 0.3 to 0.8%	2.25 to 6.0% 1.0 to 2.0%
Sulfur	Blades 3, 4, 5, 6,	–	20 to 100 ppm	300 to 10,000 ppm
Zinc	Sheaths 3, 4, 5, 6	10 ppm	<10 ppm	10 to 100 ppm

* Varies with Fe/Mn ratio. Critical level can be below 10 ppm if Fe/Mn remains above 1.

Crop logging, together with soil analyses, particularly for phosphorus and calcium, help keep the sugarcane grower's finger on the pulse of his growing crop. Adjustments in fertilization and irrigation practices and in the order in which fields are scheduled for harvest, based on the crop logging programs, unquestionably have raised yields of cane and sugar in many producing areas.

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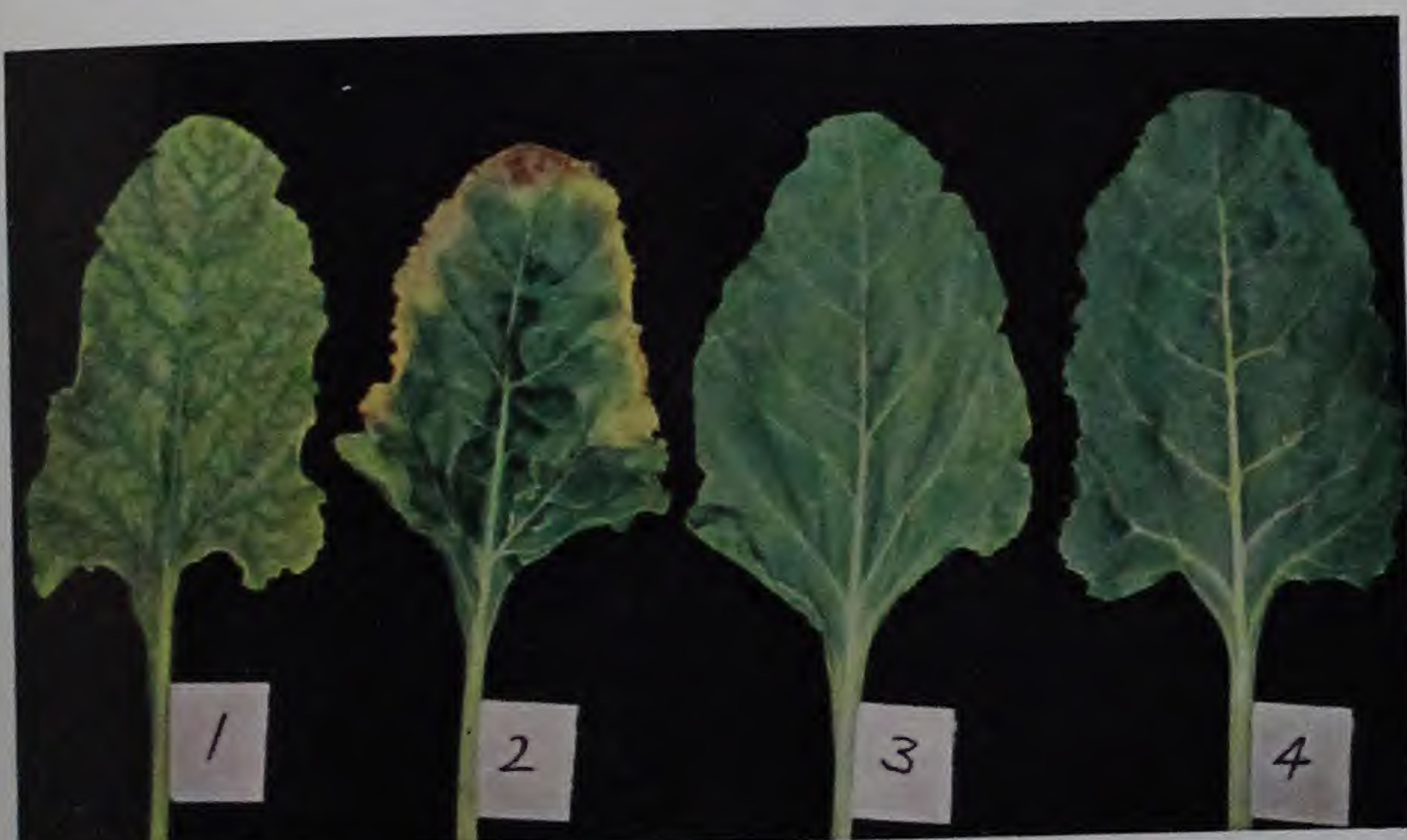
Courtesy of A. Ulrich, University of California

Plate 1. Nitrogen deficiency of sugar beets in early stages appears in chlorosis and yellowing of leaves (left). Later symptoms include death of outside leaves but new growth in centers of crown may occur (right).



Courtesy of R. L. Cook, Michigan State University

Plate 2. Leaves deficient in (1) manganese, (2) potassium, (3) nitrogen, and (4) normal are shown (left to right). Note the inter-veinal chlorosis in manganese deficiency, marginal yellowing in potassium deficiency, and uniform yellowing in nitrogen deficiency.

Courtesy of T. Wallace, Horticultural Research Station, Long Ashton, Bristol, England

Plate 3. A. phosphorus-deficient sugar beet plants have green to dark green leaves that may be fringed with a bronze or reddish coloration (above). B, calcium deficiency produces distortion of leaf blades; new leaves may collapse, blacken and die (left).

Courtesy of A. Ulrich, University of California

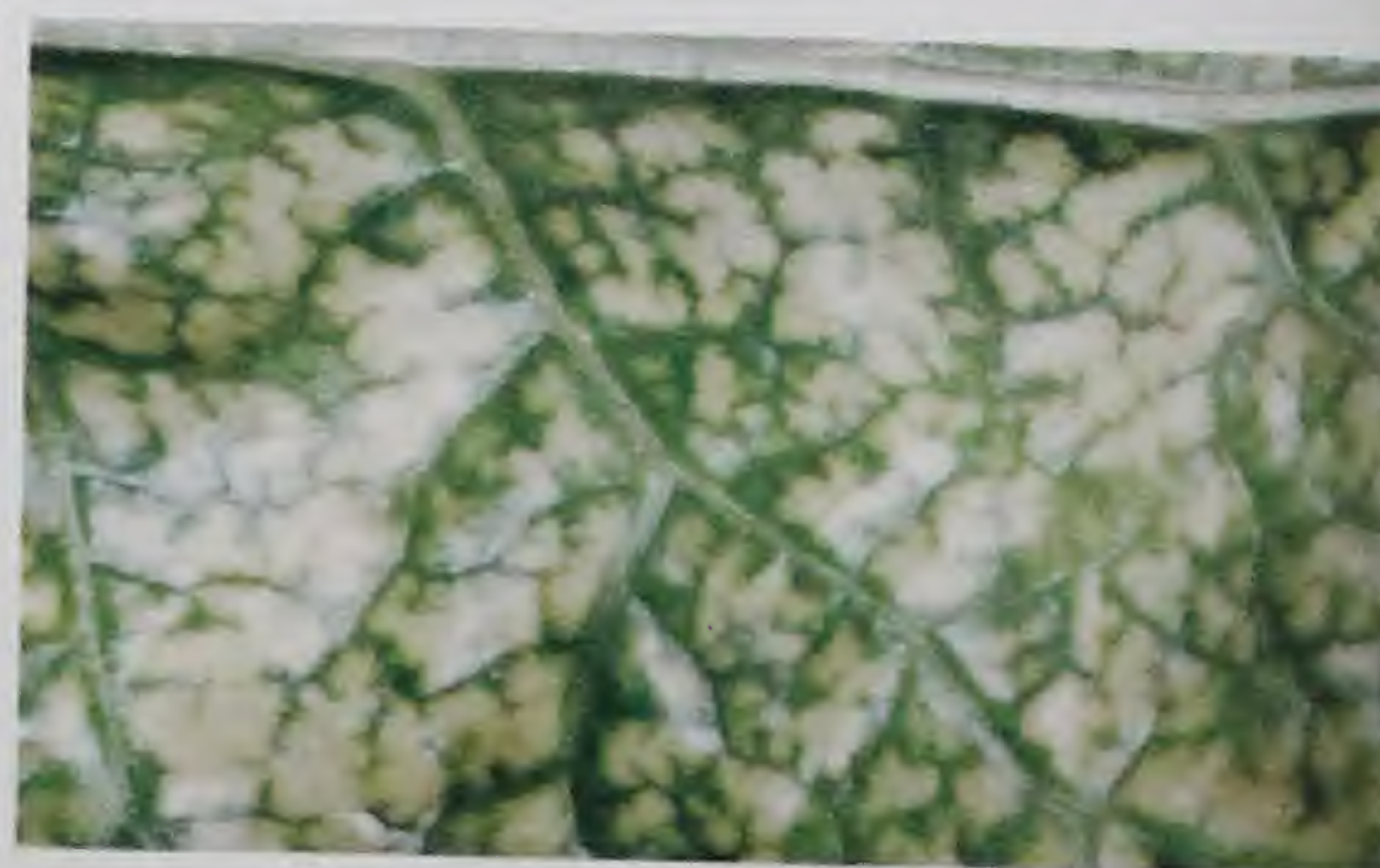
Plate 4. Magnesium deficiency appears as a patchy inter-veinal chlorosis which begins near leaf margins and in more advanced stages may appear as a leaf scorch with green midribs. Symptoms increase with age of leaf.

Courtesy of A. Ulrich, University of California

Plate 5. Sulfur deficiency symptoms appear as a uniform yellowing which tends to be more pronounced on younger leaves. Severe and mild sulfur deficiencies and a normal leaf (from left to right). A sulfur deficient plant (extreme right).


Courtesy of A. Ulrich, University of California

Plate 6. Boron deficiency causes distortion of young leaves (left). In more advanced stages (right) petioles are discolored and cross-checked and growing points die.

Courtesy of A. Ulrich, University of California

Plate 7. Iron deficiency appears first on younger leaves as a fine chlorotic mottling or bleaching. Symptoms may range from chlorosis of center leaves (left) to a uniform yellowing of the whole plant. Netting of green veins in the leaf caused by partial recovery of iron-deficient plant (right).



Courtesy of A. Ulrich, University of California

Plate 8. Zinc deficiency appears first as a general light green color. With an increase in deficiency light brown areas and necrotic spots develop between the veins which may enlarge to cover the entire leaf except the veins. Closeup of zinc-deficient leaf (right).

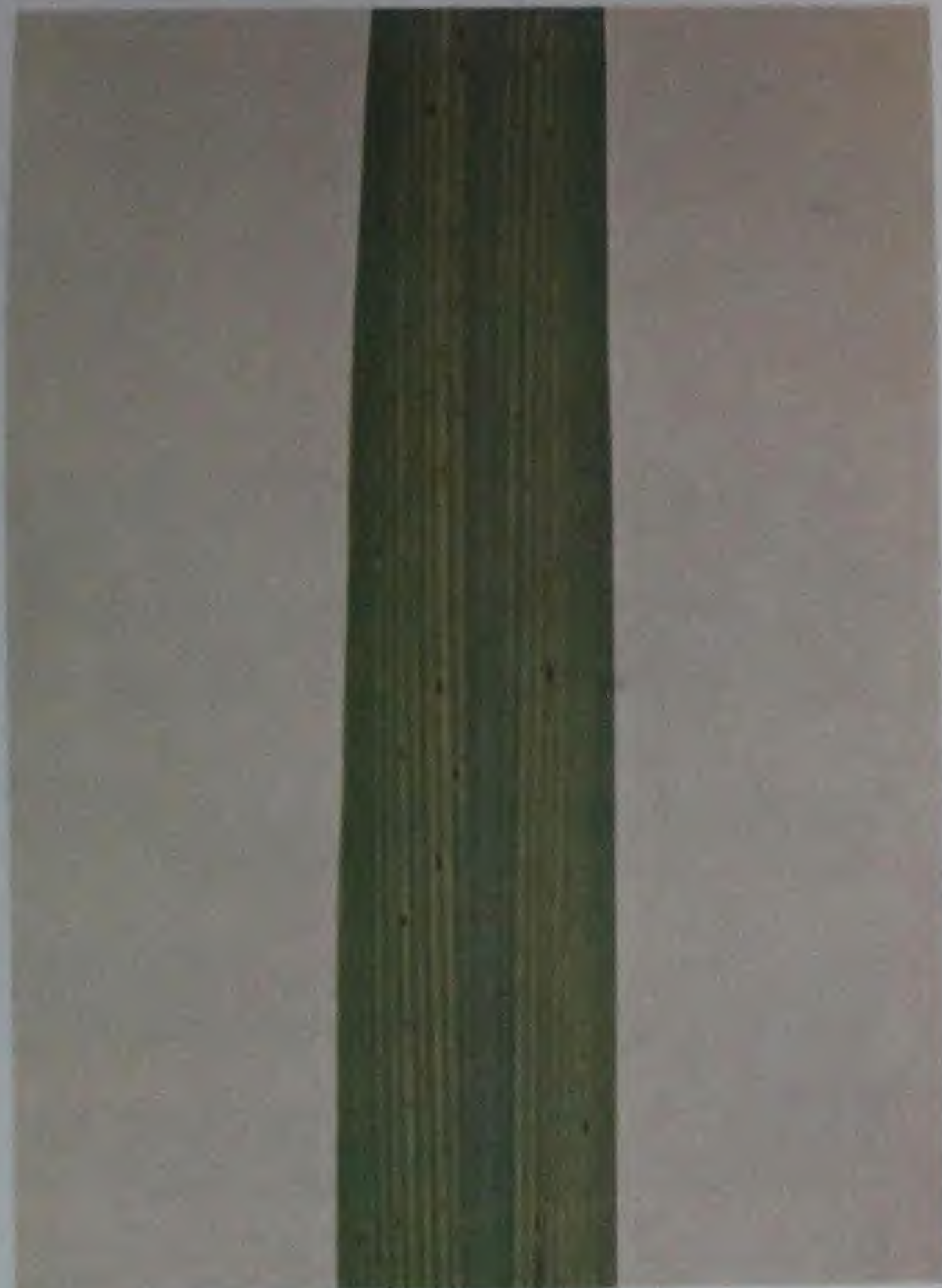
Courtesy of Roger P. Humbert

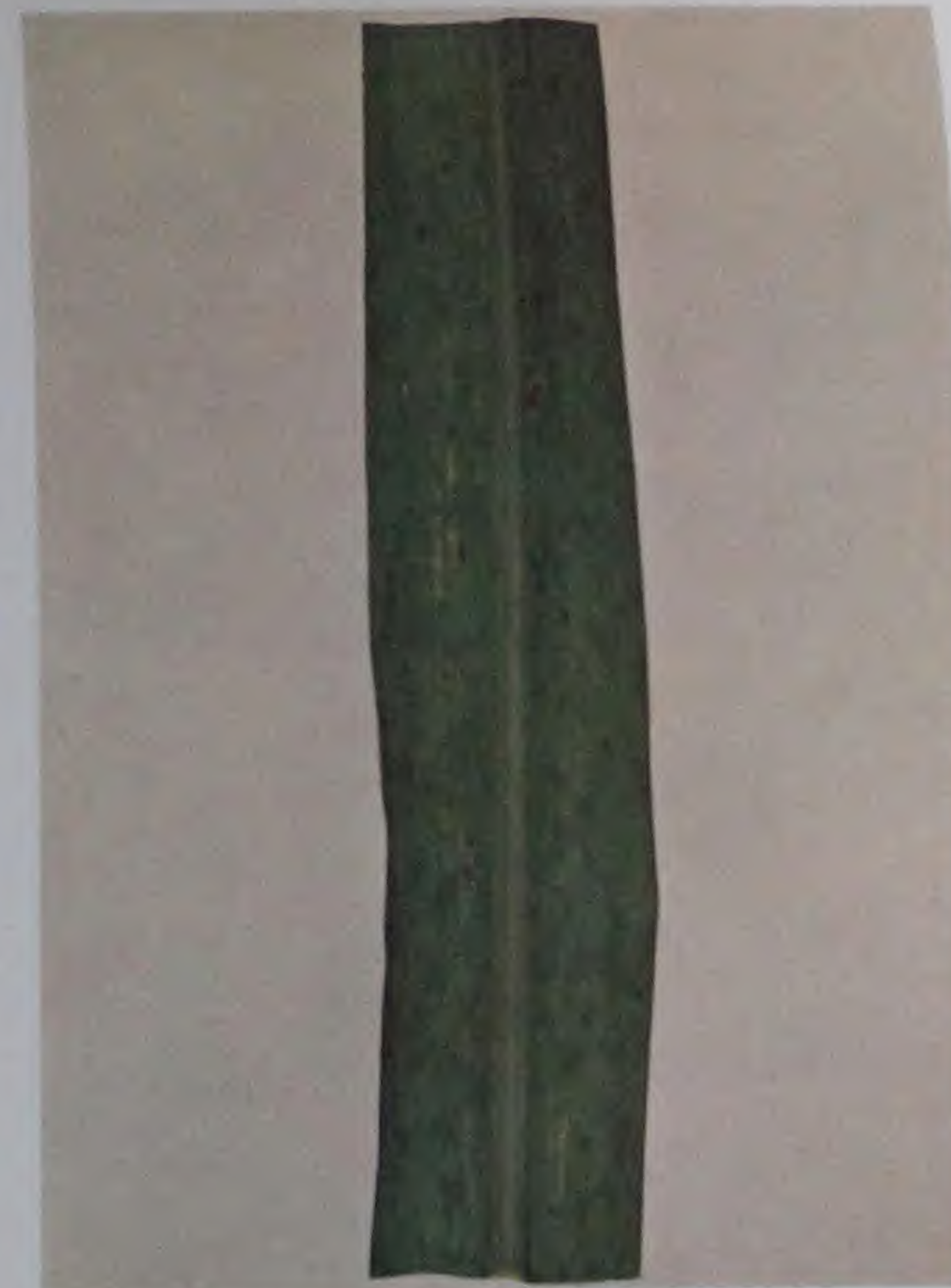
Plate 9. Potassium-deficient cane at Xicotencatl, Mexico. The older leaves show characteristic orange color with marginal firing. The younger leaves are dark green in color and appear to have developed from a common point, giving a bunched top appearance.

Courtesy of Crops Research Division, Agri. Research Service, U. S. Dept. of Agri., Beltsville, Md.

Plate 10. Germination of bud on a node of sugarcane after planting, to produce a shoot and root system.

Plate 11. Magnesium deficiency in sugarcane strain C.P. 29-116, Canal Point, Florida.





Courtesy of Crops Research Division, Agri. Research Service, U. S. Dept. of Agri., Beltsville, Md.

Plate 12. Manganese deficiency in sugarcane, strain CI. 41-223.

Plate 13. Copper deficiency in sugarcane, strain CI. 41-223.

Courtesy of Harry Evans, Bookers Ltd., British Guiana

Plate 14. Iron deficiency in sugarcane. Varying degrees of severity from normal (dark green) to severely deficient (chlorotic) striped leaves.

Plate 15. Zinc deficiency in sugarcane. Varying degrees of severity from normal (dark green) to severely deficient (chlorotic) leaves.

Courtesy of Harry Evans, Bookers Ltd., British Guiana

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